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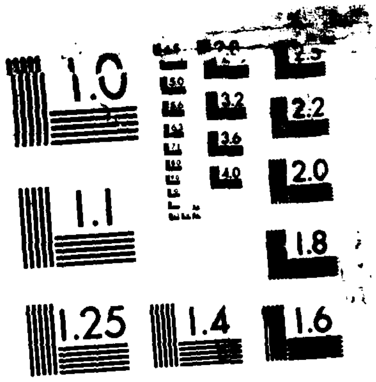

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FLYWHEEL-POWERED MOBILE X-RAY GENERATOR

Interim Technical Progress Report
(1 January 1982 - 28 February 1983)

Melvin P. Siedband
Assoc. Prof. of Medical Physics

March 18, 1983

Supported by

U.S. ARMY MEDICAL RESEARCH AND DEVELOPMENT COMMAND
Fort Detrick, Frederick, Maryland 21701

Contract No. DAMD17-82-C-2050

University of Wisconsin
Madison, Wisconsin 53706

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I. INTRODUCTION

The purpose of the U.S. Army Medical Research and Development Command contract No. DAMD17-82-C-2050 was to study the use of small flywheels as sources of power for both field and clinical x-ray systems. The main objective was to obtain information and conduct experiments which will permit the design of small, simple and reliable motor-generator-flywheel energy sources for field-transportable or portable x-ray machines. The information obtained was used to design and construct a demonstration system comprising a flywheel-powered motor generator set, a high voltage transformer, an x-ray tube, and the necessary control circuits to demonstrate the operation of the system.

The technology for the use of the flywheel as a source of power is well known and well established. However, the particular technology permitting the use of the flywheel as a source of constant potential power, adjustable in potential and pulsed for periods of 10 to 1,000 milliseconds and using commercially available alternators is not well defined. Previous commercial attempts to use the flywheel for this purpose have either been unsuccessful or have been limited to a few kilowatts.

The fundamental purpose of the study is to yield information permitting the design of very powerful 20-50 kWp x-ray machines for use under conditions where the power source capability is less than 1 kW. Success in these efforts would mean that x-rays of hospital quality could be made in the field or in remote areas, or indeed in any area where power levels are limited. The demonstration system developed in the course of this study was operated using a resistive dummy load at levels approaching 30 kWp and at x-ray tube power input levels over 15 kWp. The test circuits were shown to be capable of operating an x-ray tube under nearly optimum conditions and the test circuits, schematic diagrams, and results are described in the body of this report. The work was conducted at the Instrumentation Systems Center of the Engineering Experiment Station, with additional measurements conducted at the Dept. of Medical Physics of the University of Wisconsin, Madison, Wisconsin.

The Need for High Power Mobile X-Ray Systems

Radiographic images are limited by both noise and spatial resolution. If we attempt to raise the sensitivity of the film which is used in combination with an intensifying screen, the radiograph will show a grainy or busy image. The effect is called quantum model. If we raise the sensitivity of the screen to increase its ability to capture and convert to light incident x-ray photons, the screen will become thicker and will cause the spatial resolution to decrease. It is interesting to note that the number of photons per picture element required for detection of a particular contrast difference is the same regardless of the size of that element. For single images and objects of small size, contrast differences of less than 4 or 5% are almost imperceptible. The number of photons per picture element or pixel as a function of contrast can be estimated by the formula:

$$N = 50/(C-0.05)^2$$

where N is the number of photons and C is the contrast.

Objects of 100% contrast will require about 50 photons per pixel, while objects of 10% contrast will require about 2×10^4 photons per picture element. At 80 kVp, 1 R of radiation flux will be equivalent to about 2×10^8 photons/mm^2. Thus, the exposure required to produce a radiograph in the diagnostic range can be estimated [1]:

$$R = \frac{2 \times 10^{-7}}{(RL)(QDE)\ d^2\ (C-0.05)^2}$$

Where QDE is the quantum detection efficiency

RL is the radiolucency of the patient

D is the diameter of the object of interest in millimeters

C is the contrast and

R is the exposure in Roentgens

The following table gives some values of incident exposure estimated from this formula. Exposures are given in values that would be incident to the film screen combination if the patient or object were not present. Good geometry spacing of the x-ray tube with respect to the patient and to the film screen is required if the radiographic images are to appear normal and undistorted.

TABLE I

Exposure Estimates for Common Radiographs

Radiographic Object	RL %	Typical Contrast	d mm	Dector/QDE	Exposure
Chest	5%	8%	1.0	Film/10% screen	44 mR
Abdomen	1%	8%	1.0	Film/10% screen	222 mR
Head	1%	8%	0.8	Film/8% screen	433 mR
Head Tomo	0.5%	7%	0.8	Film/8% screen	1.95 R
Lower leg	5%	10%	0.8	Film/8% screen	31 mR
Heart Cine/frame	2%	8%	0.8	Amplifier/Film 50%	35 mR (2.1R/sec for 60 FPS)
Airport Inspector	20%	50%	3.0	Screen/TV 50%	3.2 μR

Focus to film distance of approximately 1 meter is the value in most common use. Single-phase x-ray machines operated at 80 kVp produce x-rays at a conversion efficiency at 1 meter of about 4 mR/mAs, while three-phase or constant potential machines convert tube current to x-ray power at about 7 mR/mAs. The greater the tube current in mA, the shorter will be the exposure time. A radiograph taken with a single-phase, 20 mA, small portable x-ray machine of a heavy abdomen would require an exposure of several seconds. Exposures taken of a normal chest with such a machine would require an exposure time in excess of 0.25 seconds. In any event, such long exposure times may show blurred images as a result of the normal motions of body parts caused by heart beating, breathing, etc. Small machines may have to be operated at high values of kVp for increased penetration but decreased contrast. In short, the smaller systems simply cannot do an adequate job. In addition, capacitor discharge machines are limited in overall capability, energy per exposure, which absolutely precludes their use for radiography of anything more dense than thin chest.

Presently Available Mobile X-Ray Systems

There are four common types:

1. Small power line-operated units, usually limited to 20 mA, single-phase operation, 120 VAC, 60 Hz input.
2. Power line-operated units also designed for 60 Hz, single-phase operation, but requiring the use of a 220 VAC line, capable of surges of up to 100 A, for tube currents of about 200 to 250 mA maximum single-phase.
3. Capacitor discharge units typically using two capacitors totalling 1.0 microfarads and limited to about 17 mAs equivalent output at 100 kVp. These systems function in a manner similar to capacitive discharge photoflash gun, where the capacitor is charged very slowly over a period of several seconds, and then discharged through the x-ray tube.

4. Battery-powered systems with the best of these using three 30 volt, nickel-cadmium batteries, capable of about 120 amperes for a tube input current of about 100 mA. The high voltage circuits of the best of these machines produces a constant potential across the x-ray tube for most efficient production of x-rays.

For the battery-powered system, instantaneous power is usually limited to about 10 kilowatts. The single-phase 200 mA machine is, of course, 20 kilowatts, but at single-phase has only about half the efficiency of the constant potential or three-phase machines in the production of x-rays and the 20 mA device is rated at 2 kW equivalent to about 1 kW of a constant potential system. With the exception of the 20 mA machines, all of the mobile machines are quite heavy, ranging in weight between 200 and 380 kilograms.

The principal problem in mobile x-ray machine design is that of obtaining sufficiently high power levels to permit the high exposure rates and short exposure times necessary for films of adequate information content and good stop-motion capability while keeping the apparatus small. Storage battery-powered units incorporate an invertor for converting the battery output to a high frequency voltage, which is then stepped up with a transformer to operate the x-ray tube. Currently, operation of these four types of mobile x-ray machines is marginal for stop-motion exposures or when high power levels are needed for penetration. Allowing for system losses, the 90 volt battery-powered machine, when operated at maximum output power levels of 10 kWp, requires battery currents in excess of 120 amperes. The number of cells required causes the machine to be heavy. The line-powered system at exposure levels at 100 kVp, 200 mA requires line currents in excess of 100 amperes to operate the tube and to overcome losses in the apparatus. This places a heavy burden on the power line and limits portability as special power lines are needed. The disadvantage of the capacitor discharge machine is the limited total energy storage capacity; for each 1 mAs discharged, there is a voltage drop of 1 kVp. If we assume that film darkening as a result of transit through the patient is proportional to kVp^5, then one should integrate a linear discharge to the fifth power to obtain an effective mAs, the mAs equivalent to that of a constant potential generator. The effective mAs of a 1.0 μf capacitor discharged from 100 kVp to zero is:

$$\text{mAs (eff)} = 100 \int_0^1 (1-t)^5 dt$$
$$= 16.67 \text{ mAs}$$

This low value is incapable of producing satisfactory radiographs of anything more dense than a normal or thin chest.

When better stop-motion images are required, line current or battery current requirements rise to levels beyond the capability of normal hospital wiring or that of ordinary batteries. Obviously, doubling the output of the machines will double current requirements. Operation of a battery-powered mobile x-ray machine at 400 mA, 100 kVp would require 90 volt battery currents in excess of 500 amperes, far beyond the capability of present compact size batteries, which already weigh several hundred pounds. Thus, mobile x-ray generators of most present designs cannot operate at power levels corresponding to values much above 200 mA for line-powered machines, or 100 mA for the battery-powered machines, so that the exposure time must be increased to obtain adequate quantum statistical information.

Recent work at the University of Wisconsin has shown that power levels in the 40 kW range are achievable using a flywheel-alternator system. This high-power capability offers a significant improvement over existing systems.

Advantages of Flywheel-Powered Systems

A small 5 kilogram flywheel, 30 centimeters in diameter, can store over 25 kJ at 10 krpm. At an exposure level of 100 kVp and 300 mA for 50 ms, the system requires just over 30 kW and 1500 J. The exposure reduces the stored energy by 5% and rotational velocity by about 2.5%, and the reactive force or "kick" of the system is under 30 Newton-meters (about 7 foot-pounds). By using alternators similar to those found coupled to jet engines but stripped of the high cost, high temperature, low mass components, high power output levels can be achieved. The alternator used in these experiments is presently being used in the Army's Blackhawk helicopter and is rated at 20 kW continuous and 50 kW surge peak (30 seconds), and weighs just over 12 kilograms. If that alternator were made using commercial standards, it would probably weigh about 15 kilograms. The alternator is wound to achieve maximum packing density in the stator windings and the output is three-phase star, 115/208 VAC, 400 Hz, at 12 krpm. The high frequency and three-phase connection drives a very small three-phase high tension transformer which in turn powers the x-ray tube. Operation at 320 to 400 Hz has the same relationship to many of the x-ray power components as exist between aircraft power components and common 60 Hz consumer items. The high frequency, high power components are substantially smaller and lighter in weight. Light emitting diode-photoconductive cell assemblies are used to sense flywheel/alternator shaft position. This study has shown that it is possible to use three such sensors, a digital phase shifting circuit and some solid state circuitry to drive the alternator as a motor at reasonable values of operating efficiency. Thus, the small flywheel couples directly to the alternator/motor shaft without the power losses inherent in drive belts or gearing that would inevitably occur at such high angular velocities required for successful application of this technique. Four keys to success are high frequency operation, high rotational velocity, single shaft configuration, and three-phase operation. Together, these permit the design of small transformers, the use of a small flywheel and low reactive force, elimination of causes of friction and noise for more efficient operation, and the ability to generate nearly constant potential voltage across the anode of the x-ray tube permitting more optimum operation. It is estimated that overall system weight for a complete mobile x-ray system will be under 300 pounds for outputs well in excess of 20 kW, or less than half the weight and twice the power of good commercial machines. Power consumption required will be between 500 and 750 watts.

B. Preliminary Analysis

An initial study was done in order to consider possible configurations of flywheel-powered mobile x-ray generators. Technical information was collected from various suppliers of both military and commercial alternators and consultation was sought with colleagues in the Department of Electrical and Computer Engineering. It was felt that the needs for radiography in the field could be best met by more powerful machines operating at very high efficiencies, capable of producing high resolution, high contrast, stop-motion images. Eventually, by the use of modern solid state circuits, machines in the field would have all of the features and capabilities of hospital-based x-ray machines; and that the principal technical issues to be resolved were:

1. Operation of an efficient alternator as a phase-controlled motor. Alternators are optimized for their functions as alternators and make rather poor motors. It was necessary to study their characteristics as motors, make the necessary measurements and develop circuits to permit their operation as motors at reasonable limits of operating efficiency.
2. Alternator Field Control. Field control of the alternators had to be studied in terms of operation of the alternator in such a way that control of the field current could be used to set the output voltage of the high tension transformer as a function of shaft speed, desired output voltage of the x-ray tube, operating current of the x-ray tube, and dynamic compensation for the expected drop of output voltage as a result of the inherently unstable operation of the system when operated at 3 to 5 times normal operating power for pulse output durations of less than 1 second.

3. Three-Phase, High Frequency Transformer Design. A three-phase, high frequency transformer capable of operation of up to 125 kVp and 500 mA had to be designed for use with this system. Unexpectedly, this turned out to be the easiest task as it was a case of classical textbook design which worked exactly as predicted.

4. Ancillary Circuits for Logic and Control. Control and supporting circuitry had to be developed to control the x-ray tube filament, the x-ray tube rotor, exposure timer, and the various control and interlock circuits to permit simple operation of the system by an x-ray technologist. In an ideal situation, the system would be connected to a power source and turned on. Control circuits would automatically cause the system to start the alternator in the motor mode, sensing shaft position, and applying power to the three-phase stator windings to start the rotation of the flywheel from a standstill. As the flywheel increases in speed, the driving phase angle would be shifted to maintain motor driving efficiency. Further increases in shaft speed would result in further phase shift until the flywheel reached its maximum operating speed of approximately 9500 rpm and stabilized at that speed. The operator would then preset the tube operating voltage, current and exposure time. The operation of the two-step exposure switch would cause the system: Step 1 - changeover from motor mode to alternator mode, rotate the tube anode, set the tube filament, check the interlock, and Step 2 - pulse the alternator field and make the exposure. Release of the switch causes the circuits to revert to the motor drive mode.

Principles of Operation

In the Wisconsin flywheel system, the emphasis is on energy storage through higher angular velocity rather than using a large flywheel. From first principles, the energy E stored in the flywheel is given by:

$$E = I\omega^2/2$$

where I is the moment of inertia and ω is the angular velocity. Differentiation and division by the original expression gives:

$$dE/E = 2d\omega/\omega$$

Thus, a 10% change in energy gives about a 5% change in speed.

During an exposure, the power, P, withdrawn for the exposure is related to the energy by:

$$P = dE/dt$$

$$= I\omega d\omega/dt$$

The reactive torque, T, is given by:

$$T = P/\omega$$

For a given power level, the reactive torque is reduced by using a higher angular velocity.

For example, a 5 kg flywheel 30 cm in diameter at 10,000 rpm stores over 25 kJ. At exposure levels of 100 kVp and 300 mA for 50 mS, the system requires approximately 30 kW and 1500 Joules. The exposure will reduce the stored energy by 5% and the flywheel will slow approximately 2.5% while the reactive force on the system is about 28 Newton-meters (approximately 7 foot-pounds). As the reactive force is low enough, complicated schemes of paired counter-rotating flywheels are obviated.

Stress Limits

Flywheel stress also places limits on the rotational velocity and flywheel radius. For a rotating disc with a hole, the maximum stress, σmax, may be estimated by:

$$\sigma max = \frac{3}{4} \rho R^2 \omega^2 \qquad [2]$$

where $\rho = 7.8 \times 10^3 kg/m^2$ for steel

let R = 0.15 m (radius) and ω = 10 krpm,

$\sigma max = 1.4 \times 10^8 \; N/m^2$

σ = 22,000 lb/in^2 approx.

Localized stresses, due to machining and mounting can increase this value. Common steel plate has a yield point of about 50,000 lb/in^2. However, a prudent choice of steel can offer a wide margin for safety. The Wisconsin flywheel system uses a 4340 alloy steel flywheel, normalized and tempered with a yield point of approximately 125,000 lbs/in^2. High speed testing and low housing clearance reduce the risk associated with material failure. In general, conventional grease-packed bearings have a ball speed limited to 18 m/sec. This limits the shaft speeds to the 12,000 to 15,000 rpm range, depending on the shaft diameter. At these speeds, the use of high grade bearings and close tolerances are necessary for low levels of unbalance [3,4,5].

<u>Alternator Limitations</u>

Flywheel speed is also limited by alternator characteristics. Alternators may show a limitation of output with speed as a result of the reactance of the stator windings. Thus, although the open circuit voltage of each stator winding is V_S, the alternator driving circuit to the load resistor R_L is:

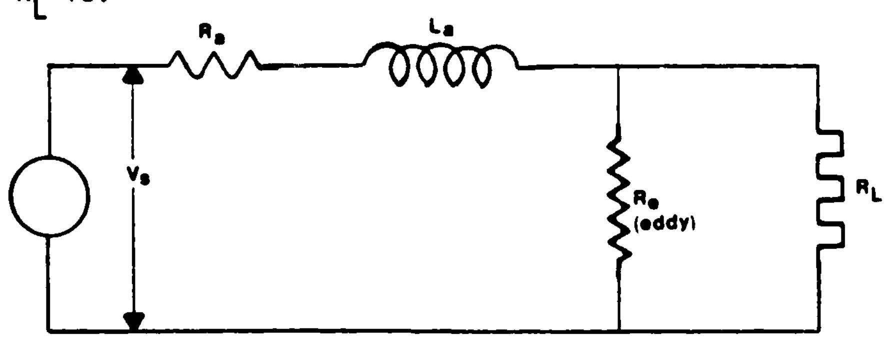


Figure 1

so that increasing the rotational velocity increases the output voltage but also increases the operating frequency. The increase in inductive reactance, a function of frequency, in series with the load resistor, and increased shunt losses due to eddy currents, impose a limit on practical operating speeds.

The effect of the eddy current loss is to reduce the power available to the load by an effective shunt resistance, R_e, which is a decreasing function of ω and depends on construction details of the alternator.

From the simplified circuit diagram (Fig. 1):

$$V_S = \frac{R_L \| R_A + R_A + DL_A}{R_L \| R_E} V_D$$

where D = d/dt.

Simplifying:

$$V_S = \frac{R_L R_E + [R_L + R_E][R_A + DL_A]}{R_L R_E} V_D$$

Assuming V_S has the form, $V_S = A e^{i \ t}$, then V_S increases with ie and V_D has the form, $V_D = B(\omega)e^{i \ t}$ where:

$$B(\omega) = \frac{R_L R_E A\omega}{R_L R_E + [R_L R_E][R_A + i L_A]}$$

Since R_A is usually small when compared to R_L and L_A,

$$B(\omega) \approx \frac{A\omega}{1 + [\frac{1}{R_L} + \frac{1}{R_E}] i\omega L_A}$$

$$\approx \frac{}{\frac{1}{\omega} + [\frac{1}{R_L} + \frac{1}{R_E}] L_A i}$$

At high speeds:

$$|B(\omega)| \approx \frac{A\ R_L}{L_A\ [1 + R_L/R_E]}$$

At low speeds:

$$B(\omega) \approx A\omega$$

When operating at low speeds, the voltage increases with ω linearly. As ω increases, the term increases:

$$\left(\frac{1}{R_L} + \frac{1}{R_E}\right) \omega L_A$$

and becomes much greater than unity. At this point, the output becomes:

$$|B(\omega)| = \frac{A\ R_L}{L_A\ [1 + R_L/R_E]}$$

$$\approx \frac{A\ R_L}{L_A}$$

when $R_E >> R_L$

In this range, the output is relatively constant.

As the speed increases further, eddy current losses increase with a decrease of $R_E\ (\omega)$. When R_E reaches the magnitude of R_L, the output drops. When driven to high levels, the output would be:

$$|B(\omega)| = 1/2\ \frac{A\ R_L}{2}$$

when $R_C = R_L$

This is a limiting case; however, it is seen that the output would decrease if the eddy losses became severe.

There are thus three ranges of output:

1. Linear range where the output increases rapidly with ω.
2. Constant output range where the output levels off at:

$$|B(\omega)| = \frac{A\ R_L}{L}$$

3. A decrease range where losses due to eddy currents are excessive. This is diagrammed below:

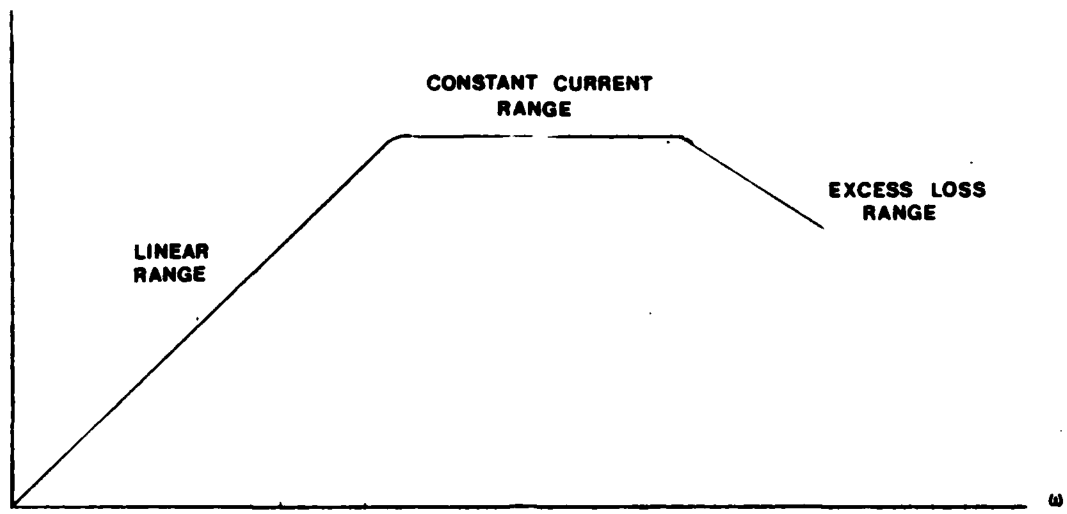


Figure 2

Flywheel Drive

The simplest way of bringing the flywheel up to speed is to use a small electric motor. This would usually involve some type of coupling, such as a flexible coupling drive, belt, gear drive, or other mechanism. At high speeds, such couplings are sources of power loss or machine vibration. It is possible to operate alternators as motors and eliminate the separate drive motors. However, unlike DC motor/DC generator systems, modern alternators do not have commutators but use a rotating field magnetically coupled through the central shaft or excited through slip rings. As three-phase or polyphase devices, they will not operate as efficient motors without the use of some form of phase-sensitive commutator capable of driving the three stator windings as a function of both shaft position and rotational velocity. The method used in this application is a form of optical encoder on the flywheel to sense shaft position.

The encoding pattern and three fixed optical sensors are used to control driving circuits for the three stator windings.

X-Ray Tube Output

X-rays are produced by two principal mechanisms in the diagnostic range: the bremsstrahlung or "braking" radiation as electrons arriving at the anode are decelerated and characteristic radiation as electrons close to the nucleus are first removed by the arriving electrons and release x-radiation as they are replaced by lower level electrons. Bremsstrahlung radiation intensity, I, is given by:

$$I = C_1 \, i \, ZV^2 \qquad [6]$$

where C_1 is a constant, i is the electron beam current, Z is the atomic number of the anode material, and V is the accelerating voltage. X-ray attenuation in the diagnostic range is proportional to $1/V^3$ approximately. Characteristic radiation is zero for $V < V_C$, where V_C is a voltage equal to the k-shell binding energy, E_k divided by the charge of an electron, e. Characteristic radiation increases with accelerating voltages above V_C. The overall effect on x-ray levels reaching the film for a particular tube and patient is:

$$I = C_2 \, i \, V^6 \text{ approximately.}$$

Differentiation and division yield:

$$\frac{dI}{I} = \frac{6dV}{V}$$

so that a 3% change of voltage will produce an 18% change at the film. The effects of ripple or non-constant mode voltage are most important.

Anode current follows the rule for temperature limited diodes where the current density, J, at the filament is:

$$J = C_3 Te^{2-u/kT}$$

where C_3 is a constant, T is the temperature, u is the work function of the filament and k is the Boltzmann constant. If constant filament resistance, R, is assumed, then a filament current, i_f, will heat the filament:

$$C_4 \sigma T^4 = i_f^2 R$$

where C_4 is a constant and σ is the Stefan-Boltzmann constant. To simplify:

$$i_f = C_5 T^2$$

To find the precision needed for control of i_f, we need to find C_6:

$$\frac{dJ}{J} = C_6 \frac{d\, i_f}{i_f}$$

and we can find:

$$C_6 = \frac{dJ}{dT} \frac{dT}{di} \frac{i_f}{J}$$

$$= \frac{u}{2KT} + 1$$

$$= 10.3 \text{ (when } T = 2800°K \text{ and } u = 4.5 \text{ eV)}$$

This can be interpreted to mean that a 1% change of i_f will cause a 10.3% change of anode current. It is obvious that filament circuit stability of better than 1% is required for good design.

The rotor control circuits operate the anode motor to cause the anode disk to spin at 3 krpm. An interlock prevents exposure until the anode is up to speed. Operation of the tube at constant potential results in uniform heat distribution at the periphery of the anode disk and permits operation at about 140% of the dissipation allowed for usual single-phase operation.

Overview of Design Objectives

The preceding discussion of exposure requirements, energy storage, alternator characteristics and x-ray tube output provide insight into a design specification. The goals were to conduct applied research to design a system:

1. Small, high-speed flywheel (10 krpm).
2. Constant potential to the tube.
3. Three-phase, high frequency (320 Hz).
4. Single shaft, low stress components.
5. Precise filament control.
6. High output (25 to 40 kWp).
7. Low input power (under 1 kWp).

II. APPLIED RESEARCH PROGRAM

The program is, essentially, a study project. The first part, an analysis summarized in the preceding sections of this report, was done as part of the preparation of the proposal. That brief analysis led to a description of an ideal flywheel-powered x-ray generator. Information was collected on alternators and technical discussions were had with colleagues on the merits of each device. The problems relating to motor control were discussed and laboratory experiments designed to obtain data. The various other tasks were listed and a schedule established. The schedule had four main sections: information collecting and research, preliminary testing, design and construction and final testing and analysis.

System Configuration

The analysis and testing led to the design of a high powered, three-phase system, using a 5 kg flywheel operating at 9500 rpm and an aircraft alternator. Tests of an older style aircraft alternator and several truck and automobile alternators were not successful as their pulsed load ratings were not more than a factor of two above their continuous ratings or they were just too big. The following sections describe the preliminary tests and the design of the major circuits of the demonstration system.

A. Alternator Testing

Purpose

The purpose of preliminary alternator testing was to determine the operating characteristics of pulse loaded, high speed alternators. The tests were aimed at determining the transient output level for several machines to determine if they might prove useful in the system.

It was commonly understood that pulse output levels could exceed continuous rating levels by several times, but data by manufacturers and the literature appear sparse on this point. It was felt that considerable savings of cost, size and weight could result from using a machine rated below 5 kVA. Thus, the early tests concentrated on evaluating several machines in this range.

The specifications of the project require a high speed alternator for the application. The required flywheel size at 6000 rpm is near the size of an auto flywheel which was felt too large for the application. A range of 8,000 to 10,000 rpm for operation was sought to keep the flywheel size small and reactive torque levels manageable.

Alternators for Testing

High speed alternators in the required power range are associated with aircraft applications, and the lower power range machines used in trucks and buses. Discussions with several leading manufacturers led to the choice of three vehicle alternators for testing. In order of increasing power ratings, they are:

1. Chrysler Corp., Model 4091 460, 12V, 100 Amp.
2. Leece-Neville Corp., Model A0012198AA, 28V, 100 Amp.
3. Motorola Corp., Model 8SC30094Z, 24V, 175 Amp.

The Chrysler machine is a 6 pole-pair machine with cast iron poles typical of auto alternators. The rotor length is short, about 5 cm. The bearings are conventional at the pulley end and a needle bearing assembly at the other. The case is die cast aluminum.

The Leece-Neville model is also a 6 pole-pair machine with cast iron poles. The rotor length is nearly twice that of the Chrysler model, approximately 10 cm. The stator is wave wound with copper ribbon. The bearings are sealed with grease lubrication. The housing is sand-cast aluminum.

The Motorola machine is similar in size to the Leece-Neville, a cast aluminum housing with a sealed bearing assembly. There are 8 pole-pairs with cast iron poles. The stator is coil wound. The rotor is approximately 8 cm in length.

Conjecture by Prof. Lipo, Dept. of Electrical and Computer Engineering, UW-Madison, was that the rotor length may be directly related to the ability to over drive the machines. To this end, the Leece-Neville offered the greatest promise of the vehicle alternators.

The aircraft alternators tested were two 20 kVA machines designed for military applications. The first machine was a Bendix model 28E2019C procured in poor condition through the Federal Property Supply. This machine is an 8 pole-pair alternator with a DC exciter which produced the rotor current. The bearing unit is sealed with grease lubrication. The rotor is approximately 15 cm long.

The second aircraft alternator tested and the one selected for the system was a Bendix model 28B262-35B. This alternator represents the state-of-the-art machine. It's rated at 20 kVA, 208 volts, 400 Hz, three-phase output at 12,000 rpm. The rotor has 4 salient poles. The unit is brushless with field current generated from rectified AC coupled to the rotor from an exciter coil in the stator. The bearing assembly is sealed with grease lubrication.

Both aircraft alternators use a quill or spline mount drive. In this arrangement, a rod is driven along the length of the hollow center of the rotor. This rod acts as a torsion bar to absorb shocks and vibrations from slight misalignment. Figure 3 illustrates the spline drive.

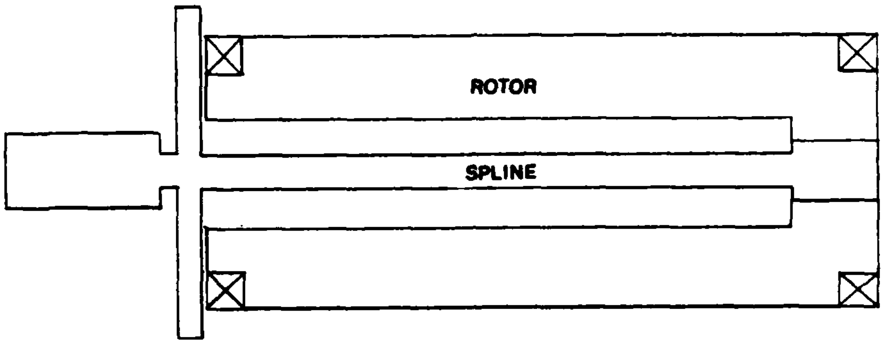


Figure 3. Diagram of Spline Drive

The spline drive mount precludes radial loads so that any driver or flywheel must have bearings or sleeves independent of the alternator.

Testing Procedures

The alternators were tested for pulse loading by either driving the unit to the desired speed by pulley or using the unit as a motor. When the desired speed was reached, the rotor field was excited to the desired level and, when stabilized, a relay was closed to switch on the load. An oscilloscope was used to check the stabilization of the open circuit voltage.

The following circuit was used to control the pulse loading.

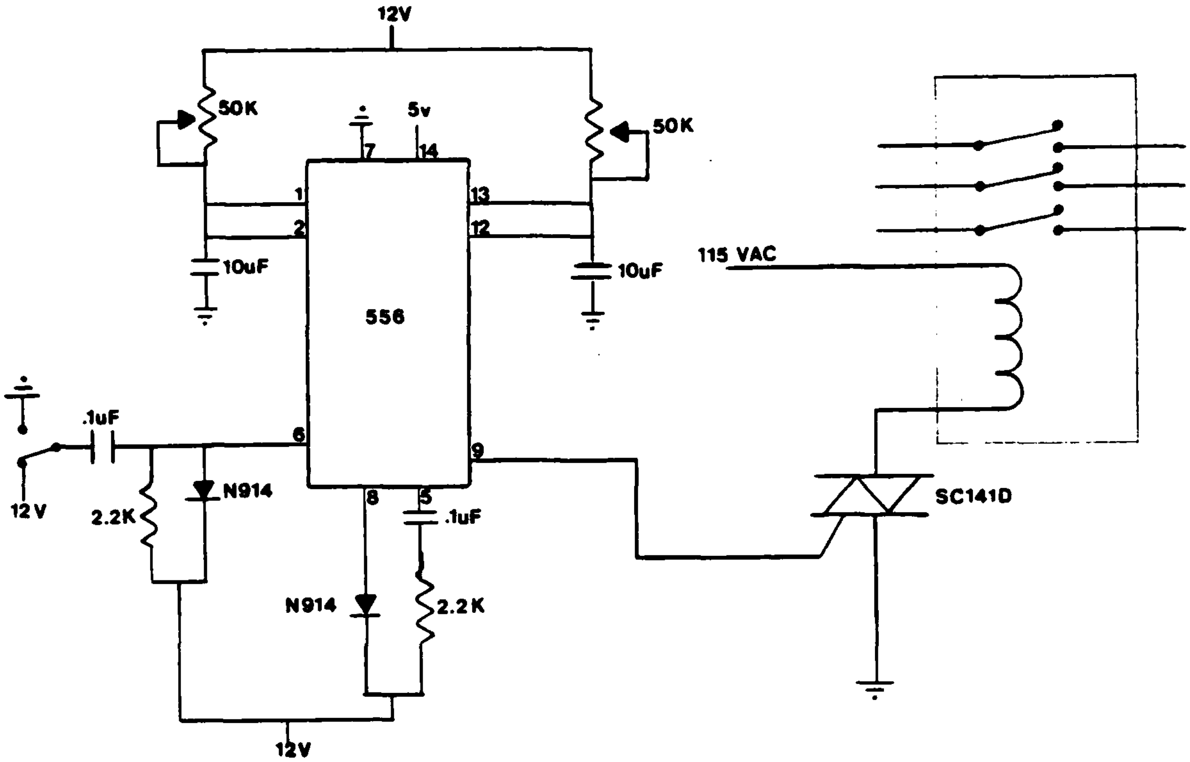


Figure 4. Pulse Load Test Circuit

For some experiments, the exposure circuit was used for much of the pulse testing.

The loads chosen for the tests varied from several ohms to 0.5 ohm. Generally, the test proceeded sequentially with the evaluation of the available data leading to a choice for a further load level.

Wye load networks were used generally. A storage oscilloscope recorded the voltage waveform. Data was recorded and when advisable, a photo was taken of the waveform.

One of the prime considerations in the evaluation of the alternators was evidence of field saturation in the transient mode. This was felt to be the limiting operating condition for the application to the mobile x-ray system.

Chrysler Test Data

The Chrysler alternator was driven to 5,000 rpm by a pulley drive. An 18 ohm/leg delta network was connected as a load. The voltage was measured with a meter phase-to-phase. The data appears below.

TABLE 2

Chrysler Data-Pulse Load

Observation #	Rotor (A)	Phase-Phase Volts RMS
1	.5	11
2	1.0	23
3	1.5	33
4	2.0	41
5	2.5	48
6	3.0	51
7	3.5	54
8	4.0	56

The data is plotted in Figure 5. The plot shows the alternator field saturated at about 2.5 ampere field current. Based on the maximum rms phase to neutral voltage 28 volts at 100 amps, the maximum output was estimated at 2.8 kW.

Motorola Test Data

The Motorola alternator was pulse tested using Wye networks of 2, 1, and 1/2 ohms/leg at 6,300 rpm. A period of 500 ms was used to stabilize the open circuit voltage before the pulse loading of 200 ms. A storage oscilloscope was used to record the waveform. The data appears in Table 3.

TABLE 3

Motorola Test Data

Observation #	Rotor Current (A)	Volts Peak to Neutral	Load/Leg Ohm
1	.5	20	2
2	.5	20	1
3	.8	30	2
4	.8	30	1
5	1.0	37	2
6	1.0	38	1
7	1.3	43	2
8	1.3	42	1
9	1.5	43	2
10	1.5	44	1
11	1.75	44	2
12	1.75	44	1
13	.5	20	1/2
14	1.0	34	1/2
15	1.5	41	1/2
16	1.75	42	1/2

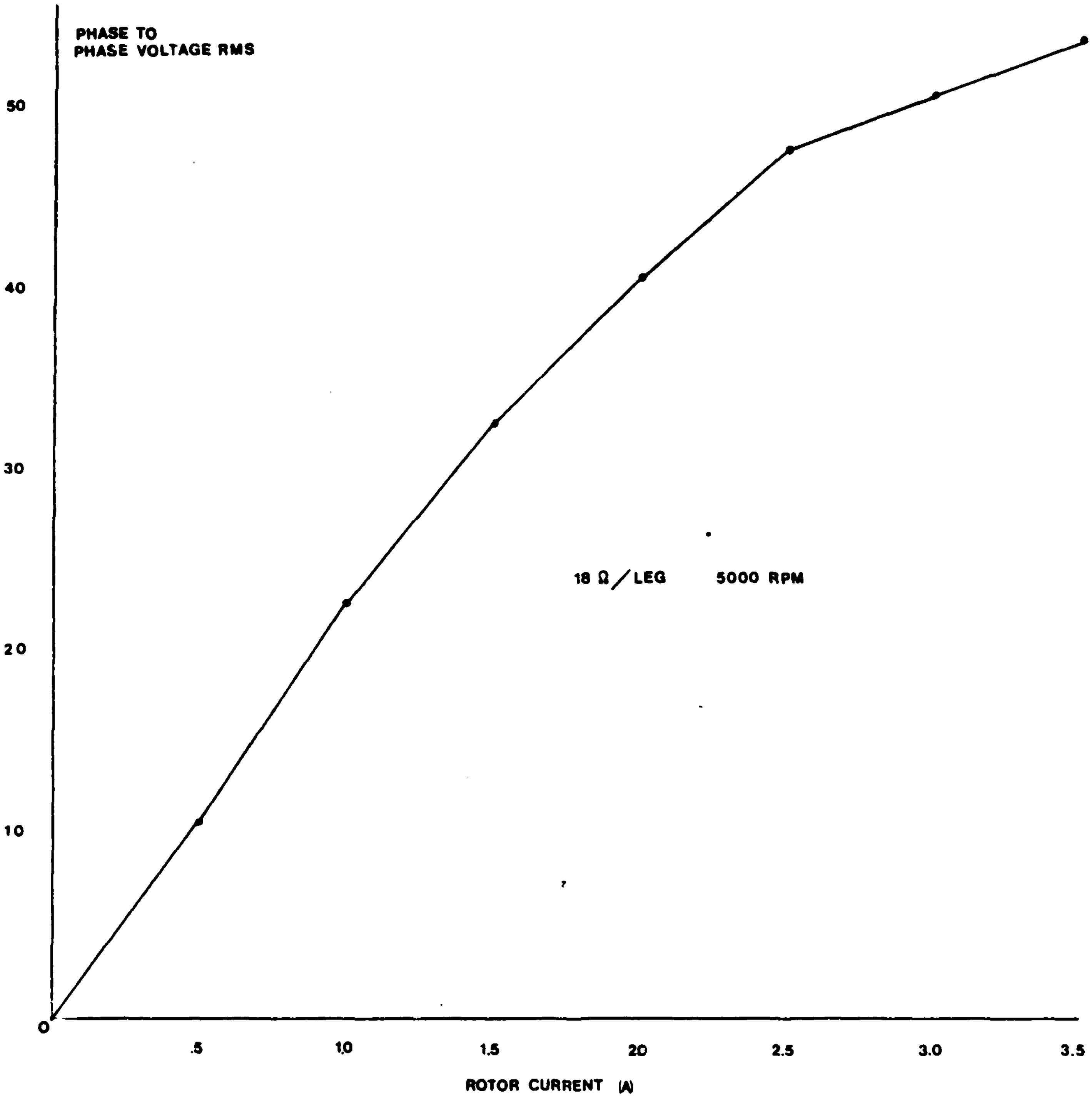


Figure 5. Plot of Chrysler Data

During the 1/2 ohms/leg tests, the effects of saturation and voltage sag during the load period combined to make control impossible for the system application. Thus, it was felt that the maximum practical output was 40 volts peak and 240 amperes total. This would correspond to 4,800 watts. With sagging conditions at saturation, 5,300 watts were observed. Loads of less than 1/2 ohm were deemed inappropriate for use in the final system, so the tests were concluded.

A plot of the data shows the saturation effects (Figure 6).

Leece-Neville Test Data

The Leece-Neville alternator was subjected to extensive testing. This was primarily due to its longer rotor and higher base impedance. During these tests, the alternator was run as a motor. This allowed for changes in speed as well as rotor current in the pulse tests. An 8 inch, 6 lb. flywheel was used to drive the alternator during the tests which were conducted as part of the system tests of the exposure circuits, motor drive circuits, and current control circuits.

Data appears in graphical form in Figures 7 and 8. The maximum output observed was 7.8 kW. At this level, there was little sag in the output in spite of operating near the saturation point. Projected to 8,000 rpm, the output would be less than 9.7 kW.

A photo of 1/2 V_{p-p} appears in Figure 9 of the test waveform at 6,000 rpm with a 1/2 ohm/leg Wye load. Little voltage sag is observed. Voltage sag was observed at lower rotor currents as seen in Figure 10.

A direct result of the high sustained output is that control of the system is possible through compensation for the voltage sag through the field current in a load forward control scheme. The final output control depends on this property, and alternators operated inside the saturation range cannot be controlled by this method.

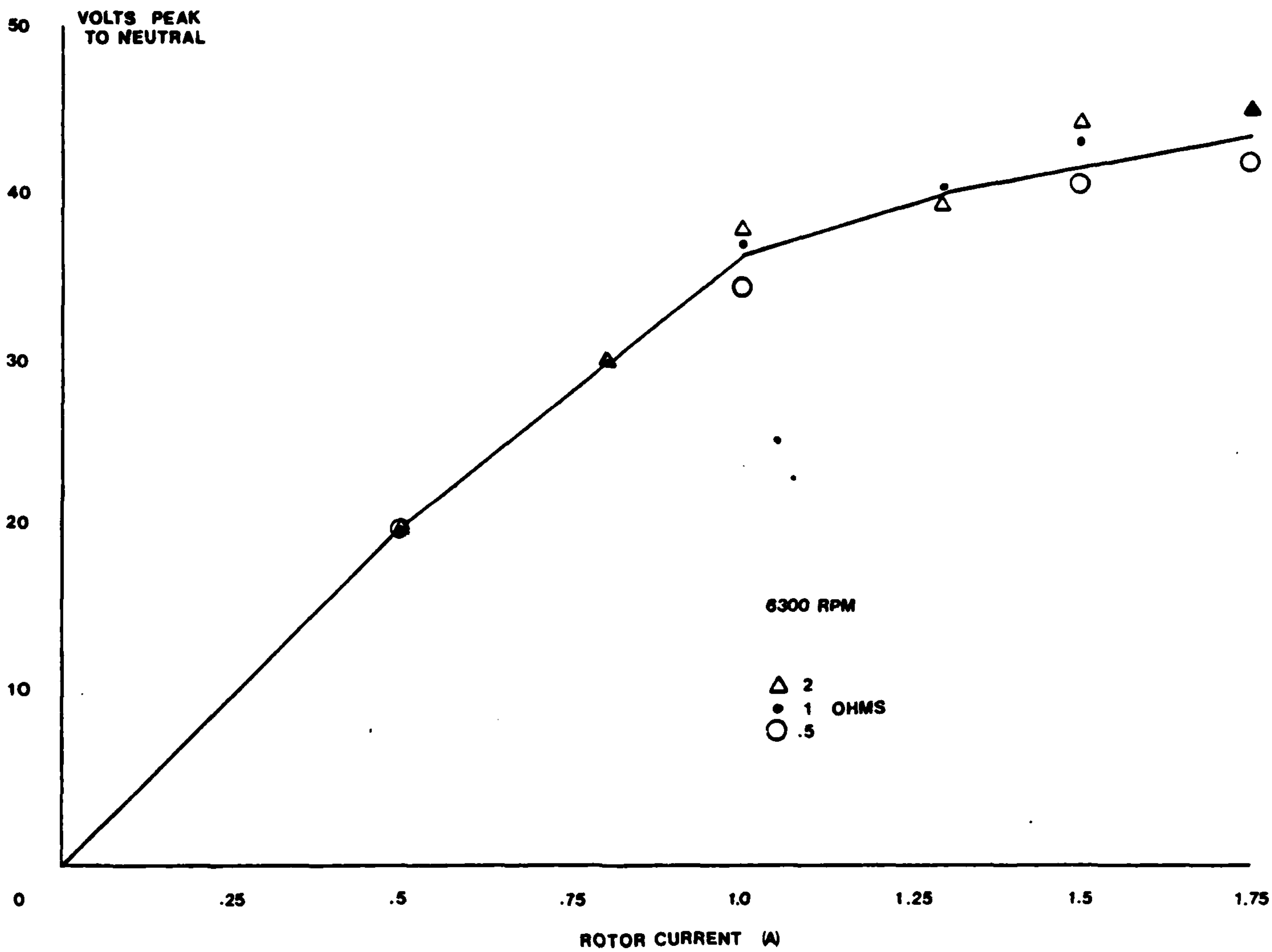


Figure 6. Plot of Motorola Data

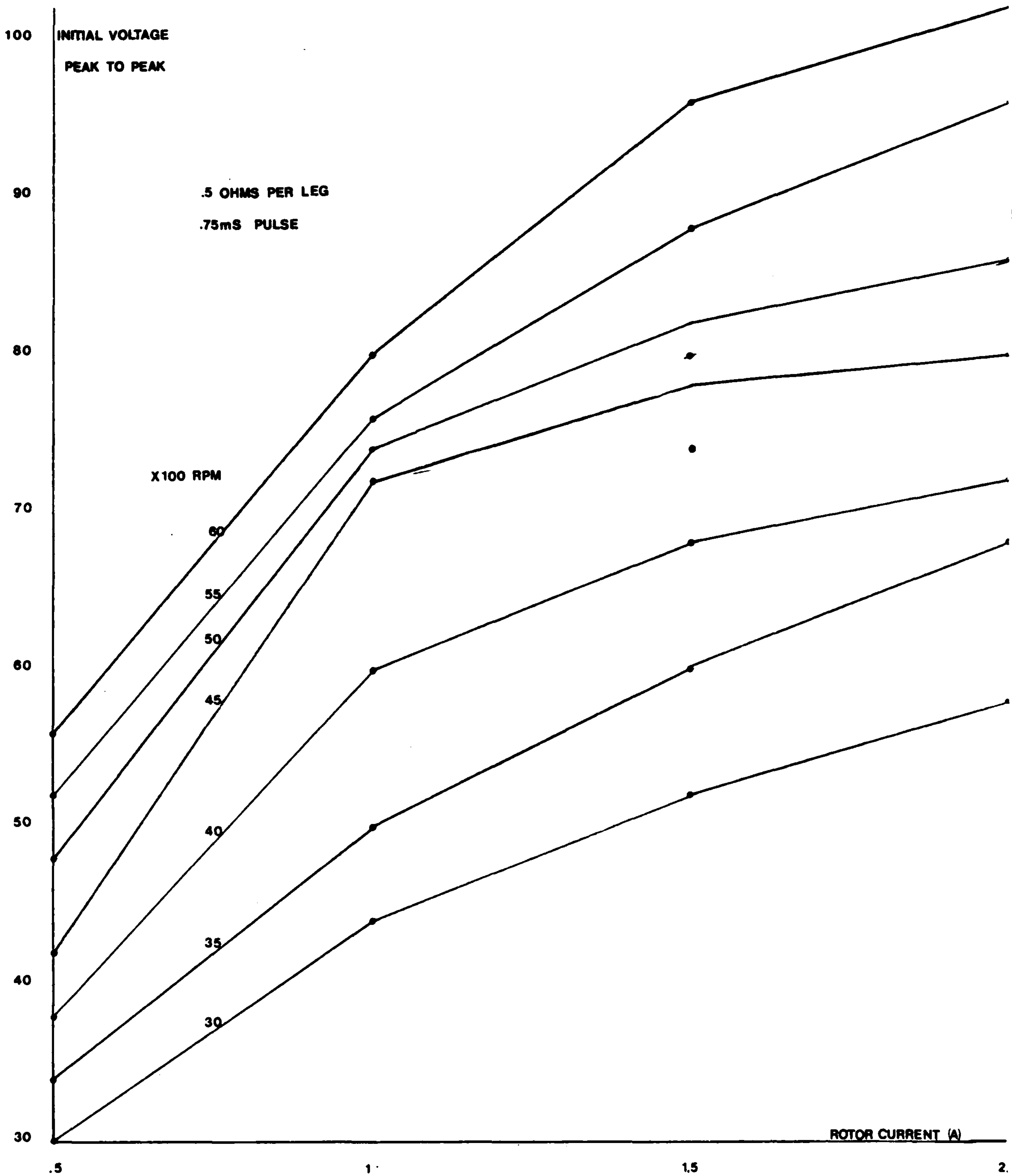


Figure 7. Plot of Leece-Neville Data

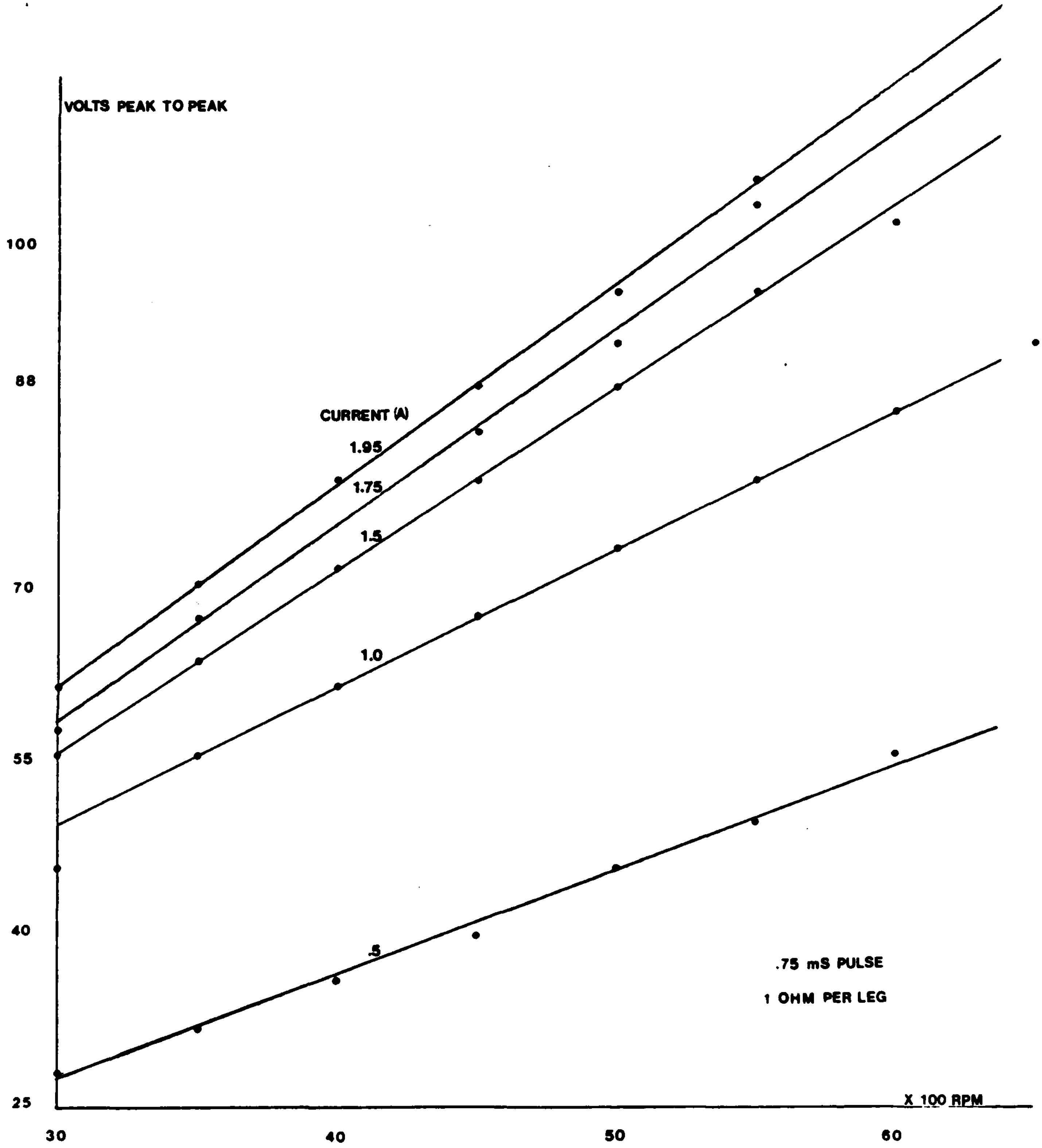


Figure 8. Plot of Leece-Neville Data

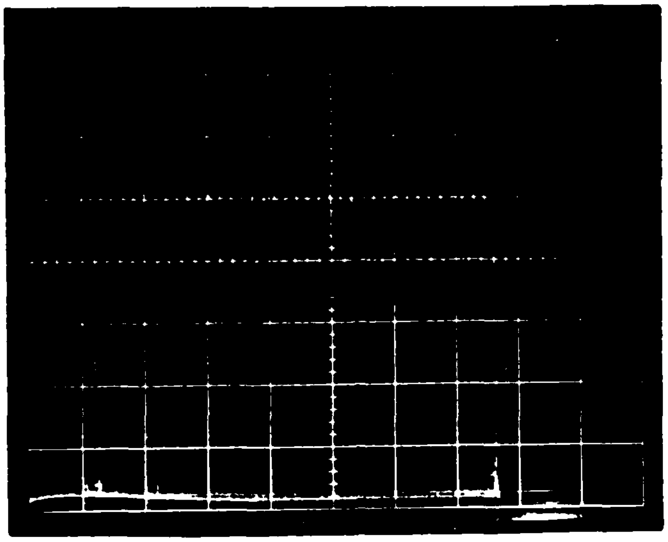


Figure 9. Output

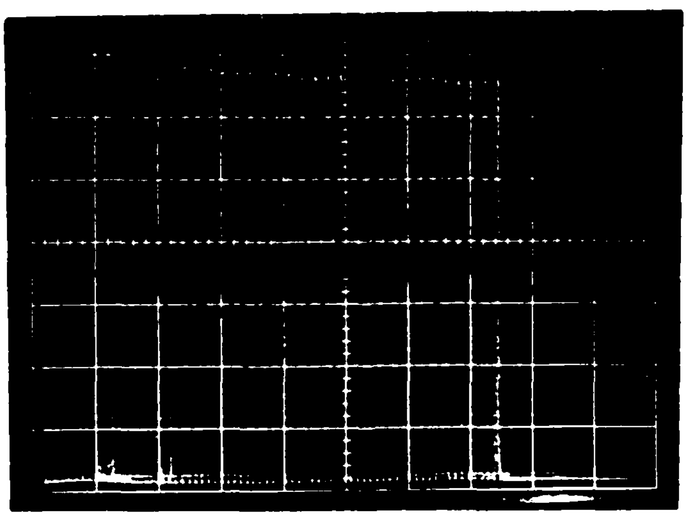


Figure 10. Voltage Sag

Bendix Test Data

Model 28E2019C arrived in poor mechanical and electrical condition. Tests were run at low speed to check for saturation effects in the rotor. The data which appears in Table 4 shows no saturation effects for field currents up to 8 amperes.

TABLE 4

Bendix Model 28E2019C Test Data
at 1333 rpm, Open Circuit

Observation #	Rotor Current (A)	Volts P-P
1	1	3
2	2	12
3	3	14
4	4	20
5	5	23
6	6	28
7	7	33
8	8	37

It was calculated that the larger rotors will allow for much higher fields in the aircraft alternators.

Model 28B262-35-B, a modern alternator made for the Army's Blackhawk helicopter, was tested. It was run up to speed as a motor and tests were run using a 1 ohm/leg load. Exciter currents are recorded. The data is listed in Table 5.

Power levels increased rapidly with operating speed. Figure 11 is a plot of the output power at 1.5 A exciter current against speed.

Voltage sag was observed in the output at low exciter currents. Control pulse tests were conducted to show that feed forward control was possible using exciter compensation. During these tests a step increase was introduced into the exciter current after the load was introduced. The result was observed on the oscilloscope. Figure 12 is a photo of the output from such a test. It was observed that the response time and the sag decay were approximately equal. This allows for control at the output level as observed in Figure 13.

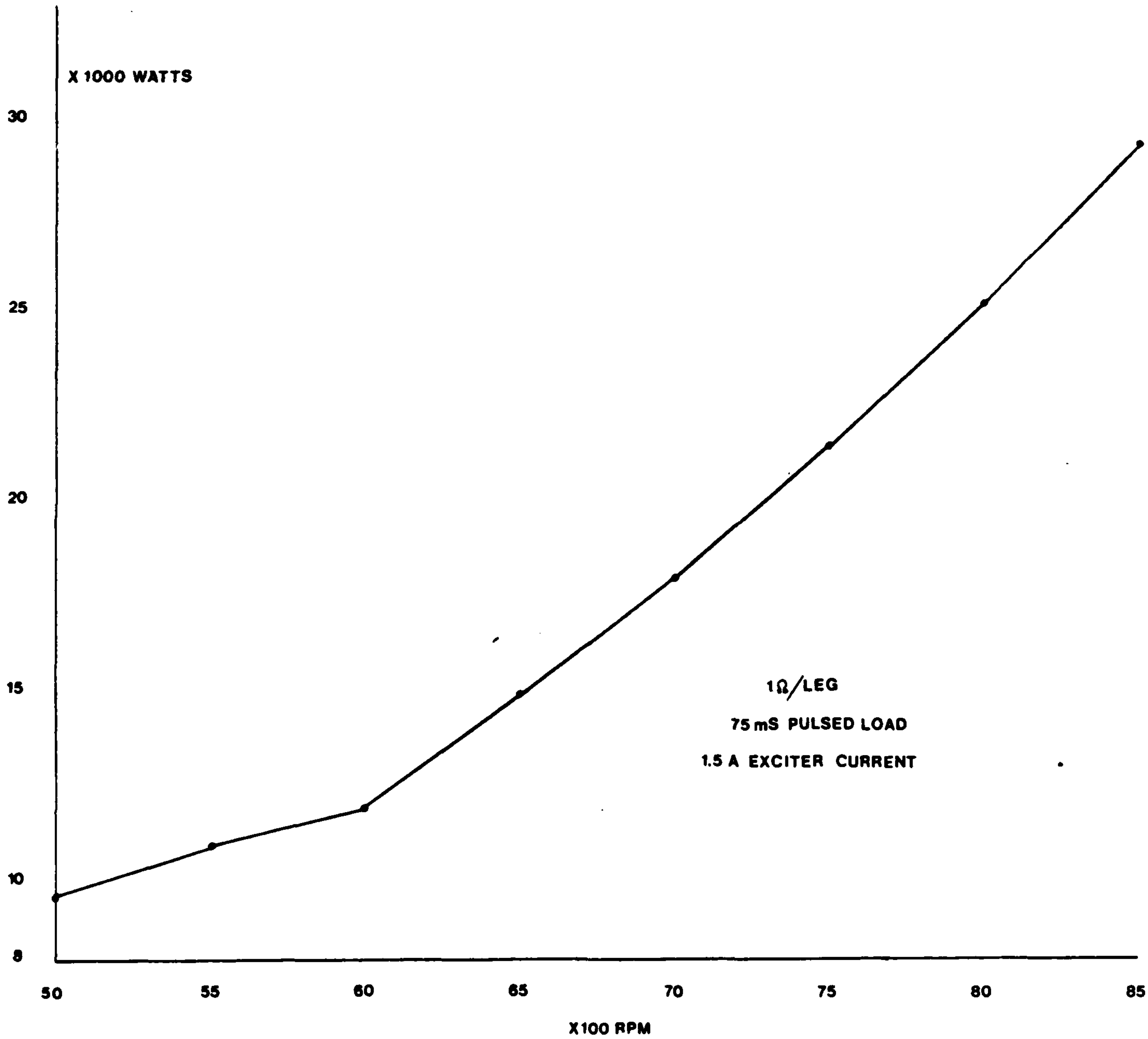


Figure 11. Plot of Bendix Data

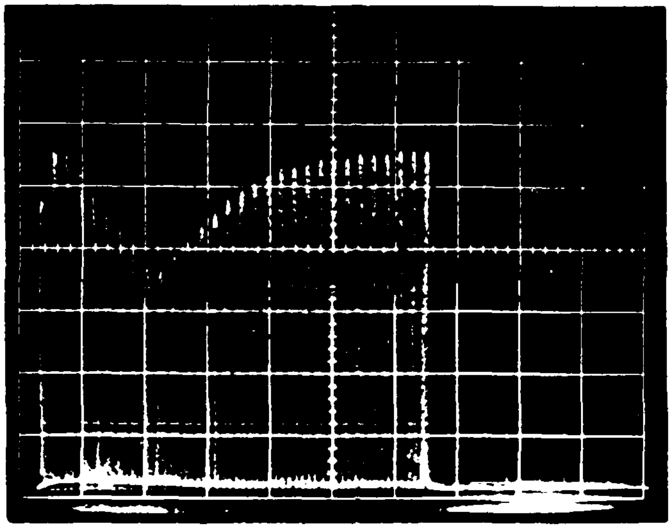


Figure 12.

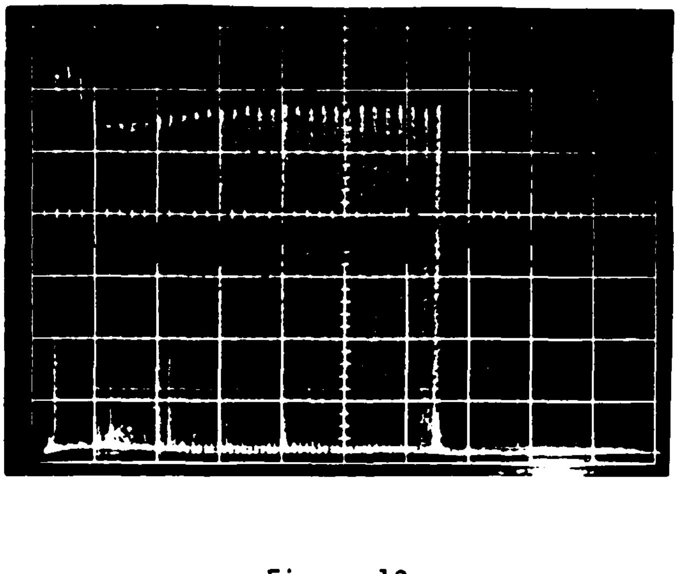


Figure 13.

TABLE 5

Model 28B262-35-B Pulse Test Data
With 1 ohm/Leg Wye Connection

Observation #	Exciter Current (A)	Speed (rpm)	Maximum Volts P-N
1	.5	5,000	33
2	.5	5,500	35
3	.5	6,000	45
4	.5	6,500	48
5	.5	7,000	55
6	.5	7,500	66
7	.5	8,000	75
8	1.5	5,000	80
9	1.5	5,500	86
10	1.5	6,000	90
11	1.5	6,500	100
12	1.5	7,000	110
13	1.5	7,500	120
14	1.5	8,000	130
15	1.5	8,500	140*

* 30 kW.

Summary of Pulse Testing

The Chrysler and Motorola alternators suffered from saturation effects and could not be driven much beyond their rating. The Leece-Neville machine was driven with good results to three times its rating. This machine appears adequate for a low-power x-ray system, less than 10 kW.

The Bendix machine is remarkable. High power levels were observed with controllable output. This alternator was used in the final system.

B. Flywheel Assembly

The assembly consists of the flywheel along with its shaft, bearings and housing. The assembly serves as the main structural unit of the system supporting both the flywheel and the alternator.

The assembly design is illustrated in Figure 14. The design calls for a cantilevered bearing mount for the shaft. This frees the flange to be cut to receive the spline of the alternator while the bearings support the flywheel. Complete drawings of the mechanical assembly are provided at the end of this report.

The Flywheel

The flywheel was made of 4340 high strength, low alloy steel plate. The steel was cut in the annealed state and heat treated, normalized and temperered, giving a final yield strength of about 125,000 lb/in. Following the heat treatment, the wheel was ground flat and mounted on the shaft and reground. Eight case hardened bolts secure the wheel to the shaft with a torque of 125 inch-lbs.

The Shaft

The shaft is constructed of 4140 high strength, low alloy steel. The steel was cut in a partially hardened state, approximately 70,000 lb/in yield. Close shaft tolerances required by the bearings necessitated a ground finish. The mating tube was fitted to the spline shaft.

Bearings

The bearings are grade 7 QOL04 high speed contact bearings, manufactured by the New Departure-Hyatt Division of General Motors. The housing and shaft tolerances are specified by the manufacturer. Great care must be taken in bearing installation. Procedures provided by the manufacturer are necessary steps which must be followed for successful installation.

Seals

The problem of seals has been only partially solved. Lip seals were used in several mountings without success. A carbon-faced seal or other form of low friction seal may be a solution. Lubrication guards are also necessary to contain the grease. Molybdenum-based, light-weight grease has proven successful and is probably better than parafin-based grease.

Housing

The housings are made of simple 2-1/2" aluminum plate. Alignment was made before the hub was cut. Centering of the housing must be within 0.0005". Once assembled, the unit must be dynamically balanced. An unbalance level of 0.004 oz. inches maximum is permitted. The balancing is done as the last operation before assembly following the painting of the optical tracks.

Optical Sensors

The three optical sensors are mounted on the movable ring on the alternator side of the housing. These sensors relay shaft position information to the electronic switching circuits. Placement of these sensors must be set to $\pm$ 1/2° at 60° apart.

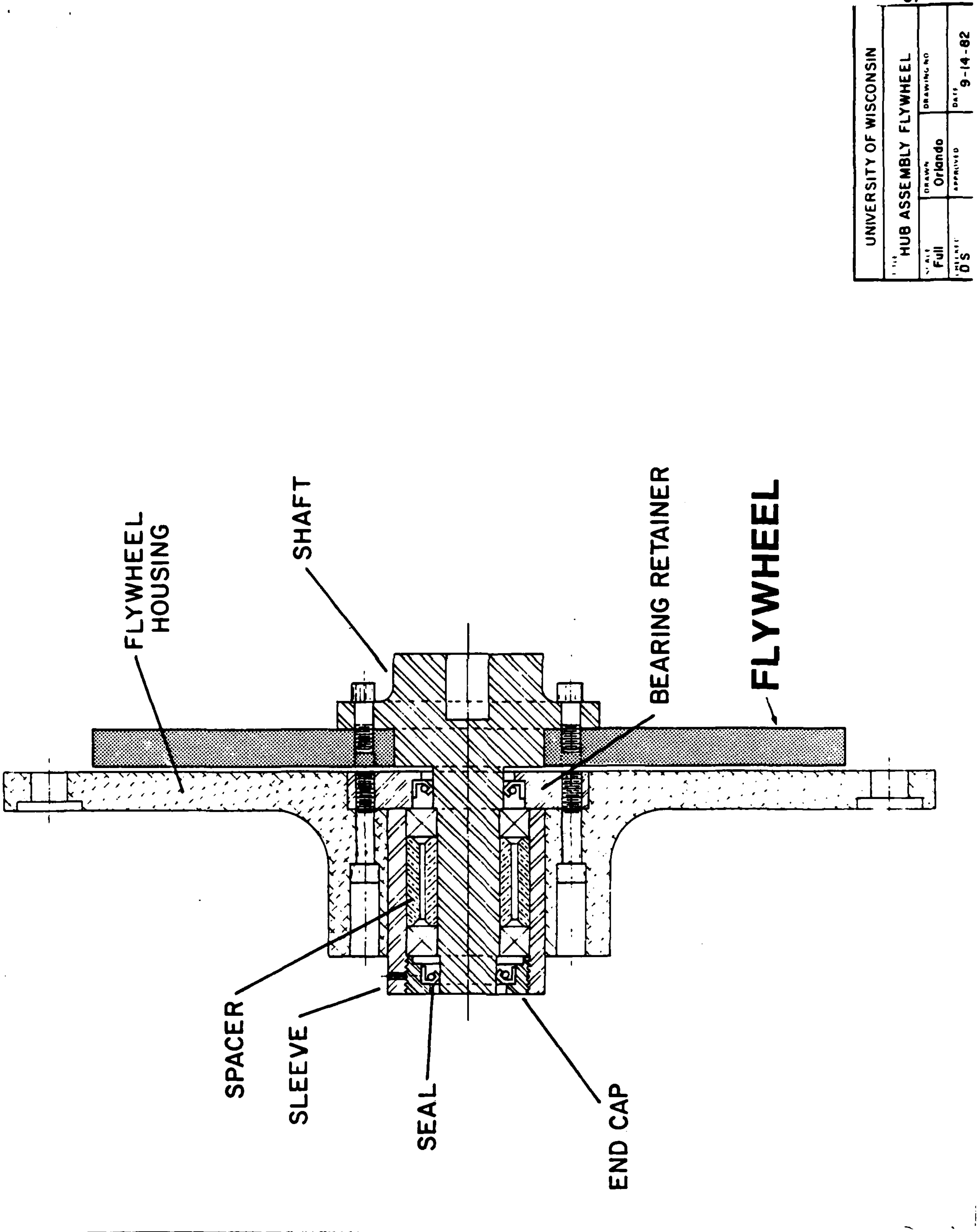

UNIVERSITY OF WISCONSIN
HUB ASSEMBLY FLYWHEEL
Full
Orlando
9-14-82
FLYWHEEL HOUSING
SHAFT
BEARING RETAINER
FLYWHEEL
SPACER
SLEEVE
SEAL
END CAP

Figure 14.

C. Motor Control System

Purpose

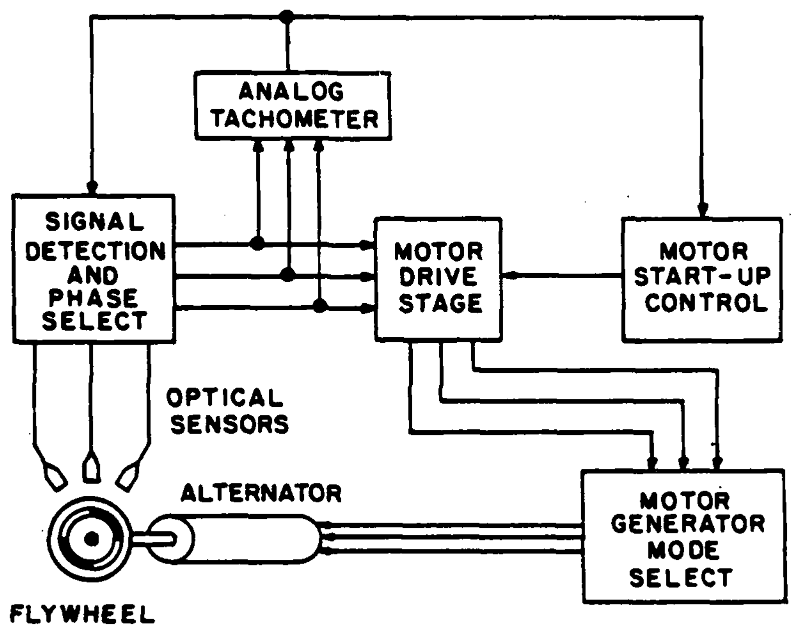
This system provides the power and control signals needed to run the Bendix alternator as a motor. The shaft position of the flywheel-alternator assembly is sensed by three optical sensors, and power signals are generated that cause the Bendix to run in the motor mode.

Operation

The flywheel is painted with a ring of four alternating black and white sectors. Three optical reflection sensors are focused on this ring,[8] each spaced 30° apart. The signals from the optical sensors are converted to pulse signals by the Signal Detection and Phase Select circuit. Phase Select refers to the fact that the drive signals to the alternator must lead the position sensing signals by greater phase angles as speed increases. By selecting the combination of the position signals and their inverses, the phase angle can be shifted by increments of 30°.

An analog tachometer circuit provides a voltage proportional to the rotational speed of the flywheel. The sensitivity is one volt per thousand rpm. The signal is used to control the phase control and the motor start-up sequence. The Motor Drive Stages switch power between the three field windings of the alternator. Switching is accomplished by power FET's.

The Motor Start-Up Control provides power to the Drive Stages. As the speed increases, there is more back EMF to the Drive Stages. To maintain the current into the field windings, the drive voltage must be increased. This is accomplished by shorting power resistors that are in series with the voltage supplied to the drive stages.

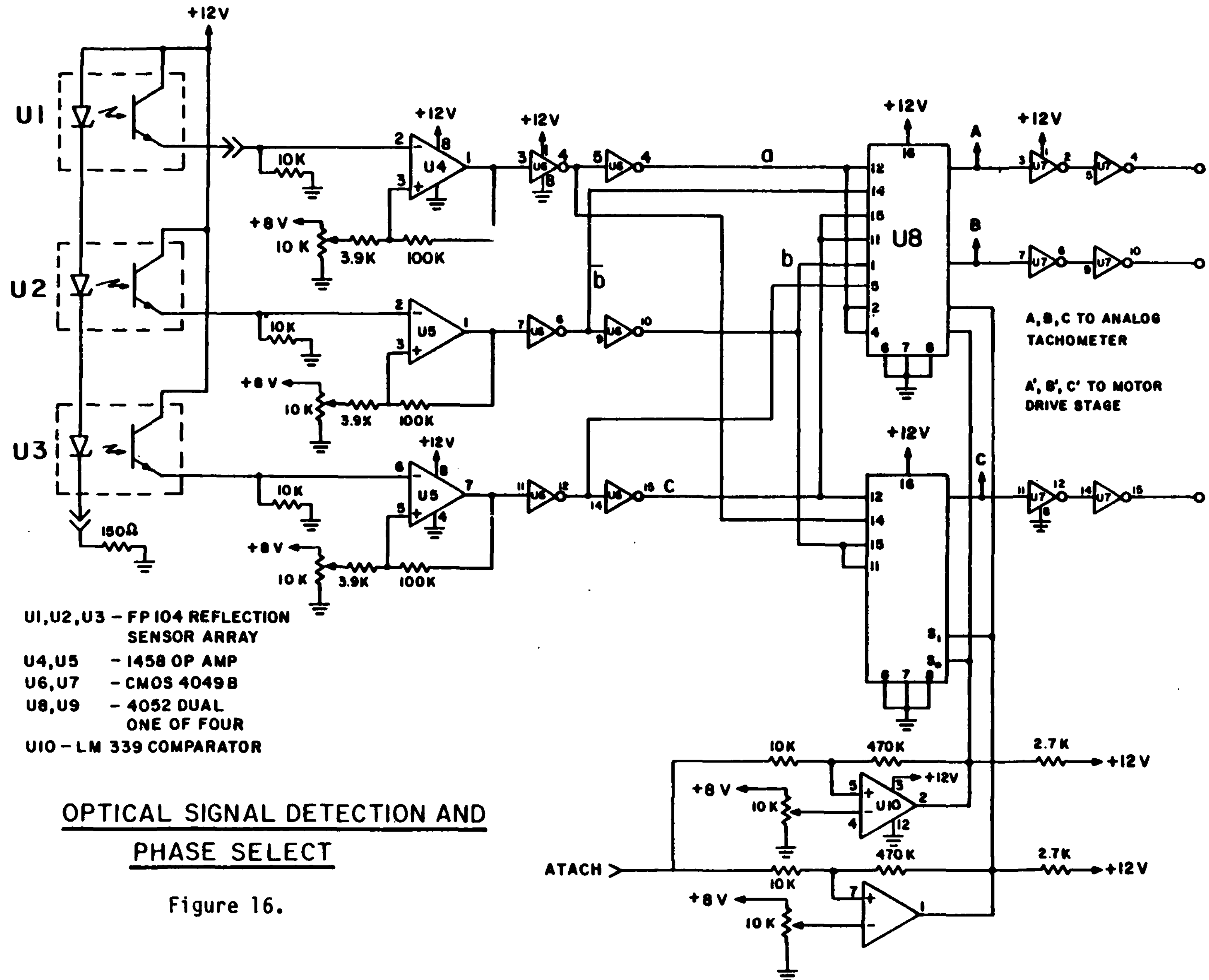


BLOCK DIAGRAM MOTOR CONTROL

Figure 15.

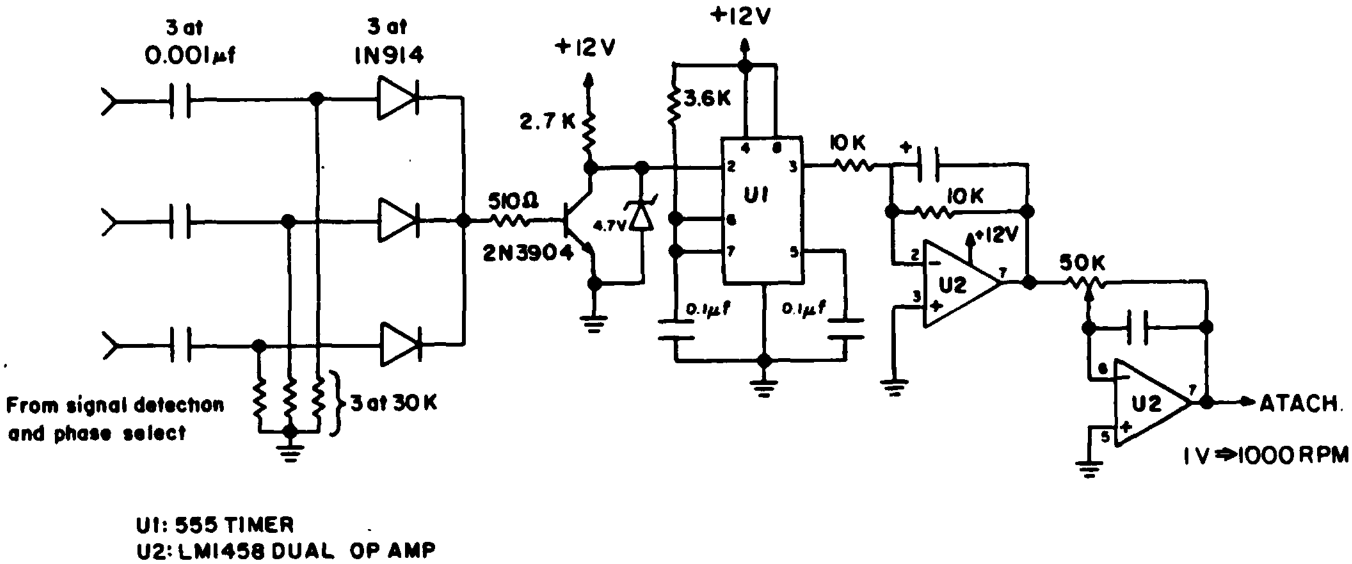
Circuit Description

1. Signal Detection and Phase Select. The position of the alternator pole pairs to the field windings is determined by three optical reflection sensors, U1-U3. The voltages from the sensors are fed into three comparators (see Figure 16). The comparator switching points can be set to allow the duty cycle of each channel to be exactly 50%. Small changes in the duty cycle greatly affect the efficiency of the motor drive. The comparator outputs are buffered through CMOS invertors, producing signals a, b, and c and their inverses: $\overline{a}$, $\overline{b}$, and $\overline{c}$. These six signals are then fed to CMOS analog data selectors, which can provide one of three signal combinations (a, b, c), ($\overline{b}$, $\overline{c}$, $\overline{a}$), or (c, a, b). These three combinations are 30 mechanical degrees apart. This then provides the phase shift necessary as the alternator increases speed. Two comparators are fed with a signal proportional to the alternator speed (see attachment) and are adjusted to toggle when the speed reaches the point where a phase shift should occur. These two comparators are connected to the analog data selectors and determine which of the three possible signal combinations are sent to the A, B, and C lines. One more CMOS invertor stage provides buffering of the signals fed to the Motor Drive Stages, A', B', and C'.
2. Analog Tachometer. Three signals from the Detection and Phase Select circuit (A, B, and C) provide the inputs for the Analog Tachometer. Three high-pass filters and diode combinations (see Figure 17) give a positive-going spike to a transistor invertor for each positive-going edge of A, B, or C. The transistor invertor supplies negative-going spikes to a 555 timer IC configured as a



OPTICAL SIGNAL DETECTION AND PHASE SELECT

Figure 16.



ANALOG TACHOMETER

Figure 17.

one-shot. The result is that each positive-going edge on the outputs of the Detection and Phase Select circuit produces a pulse of fixed duration from the 555 timer. These pulses are then fed to a unity-gain inverting integrator, consisting of one-half of a LM1458 operations amplifier, two resistors, and a capacitor. The output of this operational amplifier is a voltage that increases negatively as the frequency of the incoming pulses increase. The final stage of the circuit is an inverting amplifier of variable gain, with a small capacitor connected to provide ripple suppression. The gain of this stage is adjusted to provide an output sensitivity of one volt for each thousand rpm of the alternator.

3. Motor Drive Stage. The circuit of Figure 18 shows one of three motor drives: each is connected to one of the three alternator field windings. The windings are switched between ground and V motor by four power FET's. The FET's are connected to operate in parallel-pairs to increase current capability. Gate resistors prevent parasitic oscillations between the paralleled FET's. Zener diodes connected from gate to source prevent voltage spikes from damaging the FET's. Incoming signals from the Detection and Phase Select circuit feed a transistor inverter, which controls the FET pairs. The lower FET pair (those that switch to ground) are controlled directly from the transistor inverter. The upper pair (connected to V motor) uses an isolated voltage source which floats above the source of the upper FET's. An optical coupler switches the floating supply and is controlled by the transistor inverter. When the incoming signal is zero, the 2N3904 transistor is off, the optical coupler is off, the upper FET gates are at their source voltage and are off, the lower FET gates are pulled to 12 volts and are on, connecting the field winding to ground. When the incoming

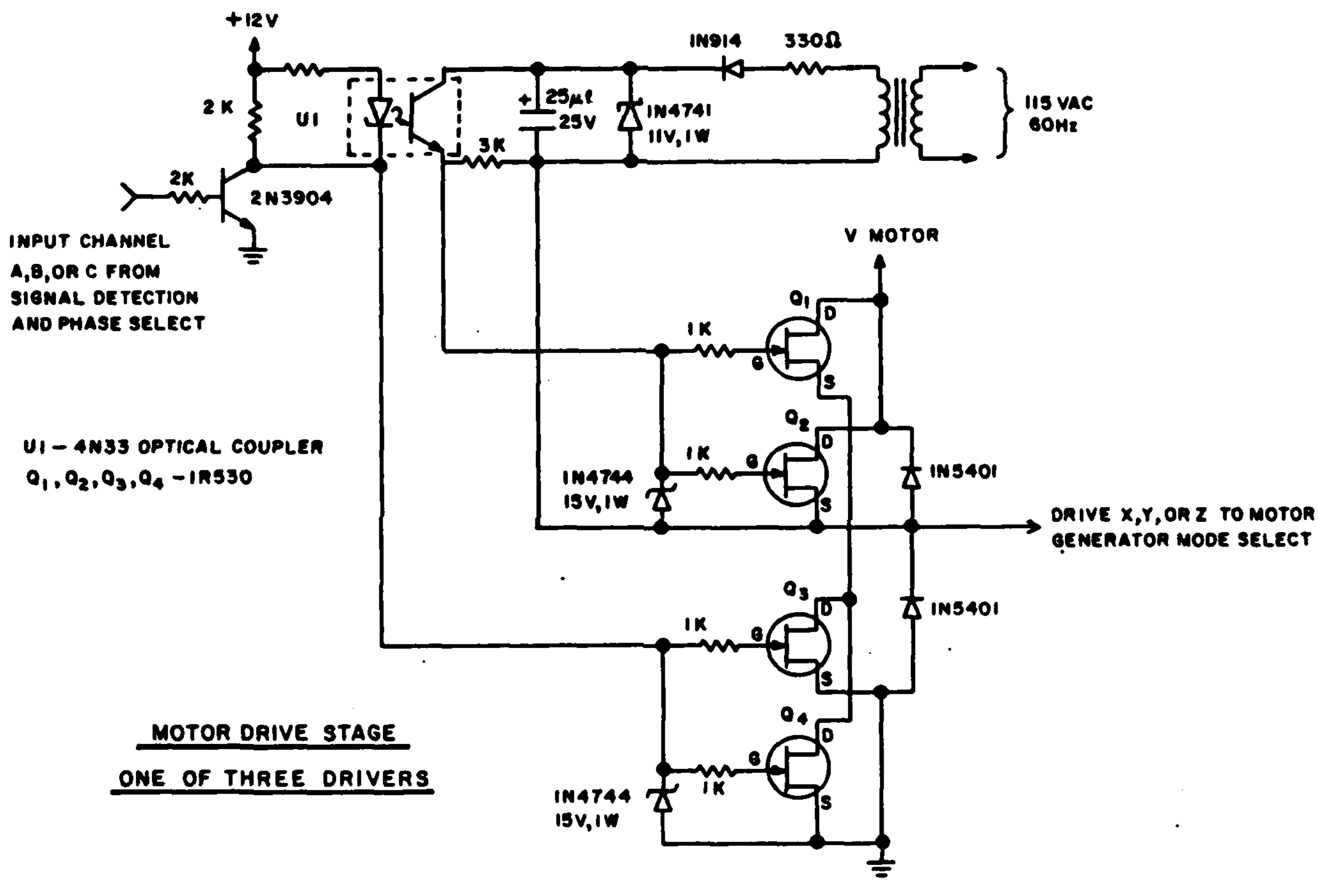
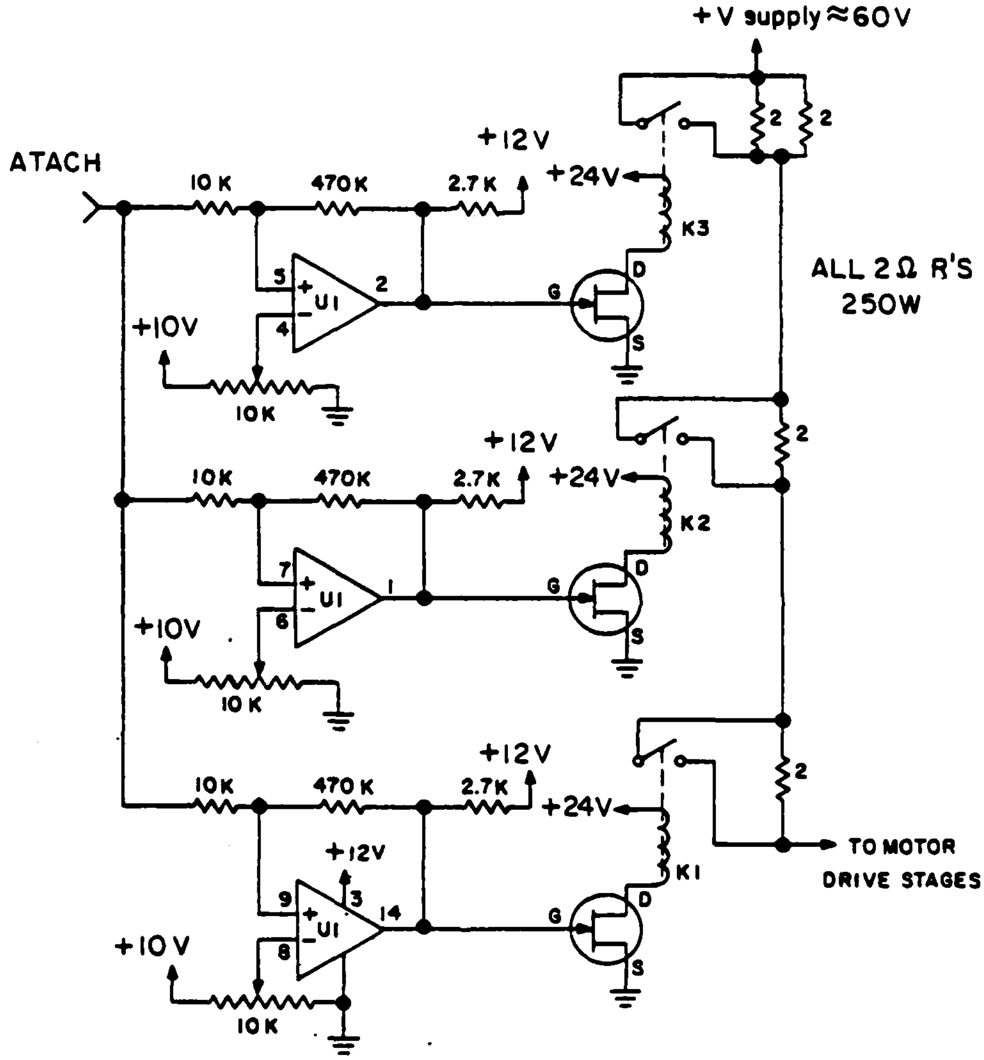

+12V
IN914
330Ω
2 K
U1
25μf
25V
IN4741
11V, 1W
115 VAC
60Hz
3K
2K
2N3904
INPUT CHANNEL
A,B,OR C FROM
SIGNAL DETECTION
AND PHASE SELECT
V MOTOR
Q1
1K
G
D
S
Q2
U1 — 4N33 OPTICAL COUPLER
Q1, Q2, Q3, Q4 — IR530
IN4744
15V, 1W
IN5401
DRIVE X,Y,OR Z TO MOTOR
GENERATOR MODE SELECT
Q3
Q4
MOTOR DRIVE STAGE
ONE OF THREE DRIVERS

Figure 18.

signal is high, the 2N3904 is on, pulling the lower FET gates to ground which switches them off; the optical coupler is switched on, pulling the upper FET gates positive, thereby switching them on, connecting the field winding to V motor. Running the alternator as a motor requires about 60 volts to maintain the speed at around 10,000 rpm. However, this voltage at low speeds would draw current from the supply in excess of 30 amps--more than the power FET's in the drive stage could deliver. To limit the start-up current, power resistors were placed in series with the DC power supply (see Figure 19). This control circuit uses three comparators connected to sense the voltage supplied by the Analog Tachometer. Each comparator is adjusted to toggle or switch at a certain speed. The comparators are connected to a power FET which controls a relay: when the Analog Tachometer voltage exceeds that preset voltage, the relay closes. The relay contacts short out the power resistor, increasing the current available to the Drive Stages. The comparators are set to maintain the average current from the DC supply to less than 10 amps.



MOTOR START-UP CONTROLS

Figure 19.

D. Digital Tachometer

Purpose

This circuit takes a digital signal from the Analog Tachometer of the Motor Drive circuit and provides a five-digit LED display of the FMG system shaft speed in rpm.

Operation

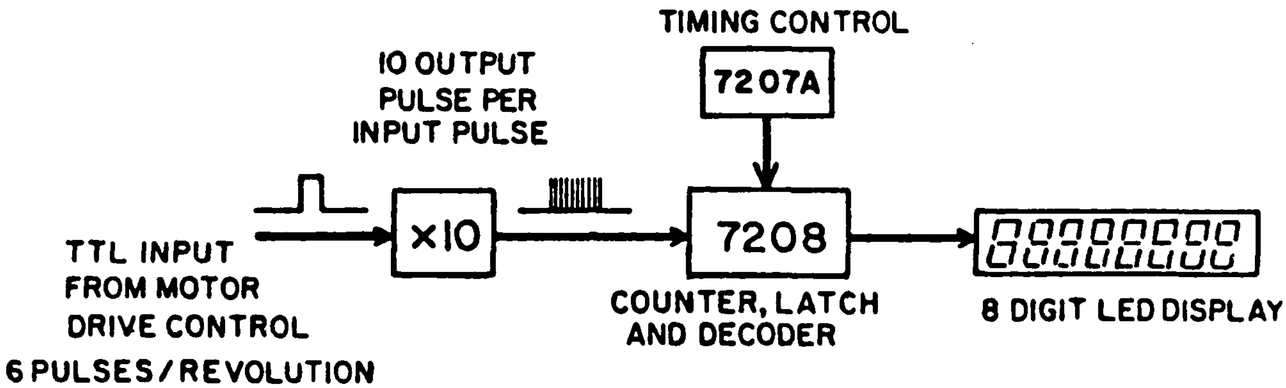
The Analog Tachometer takes the logical OR of channels A, B, and C of the Motor Drive circuit to give six pulses for each revolution of the flywheel. This signal is the input for the Digital Tachometer, as shown in Figures 20 and 21.

The 6 pulse/revolution signal is passed to a times-ten pulse multiplier circuit. By counting these pulses for a one second interval, the rpm signal of the flywheel assembly is obtained. The Intersil 7207A and 7208 combination counts pulses for one second intervals and provides a multiplexed LED display.

Circuit Description

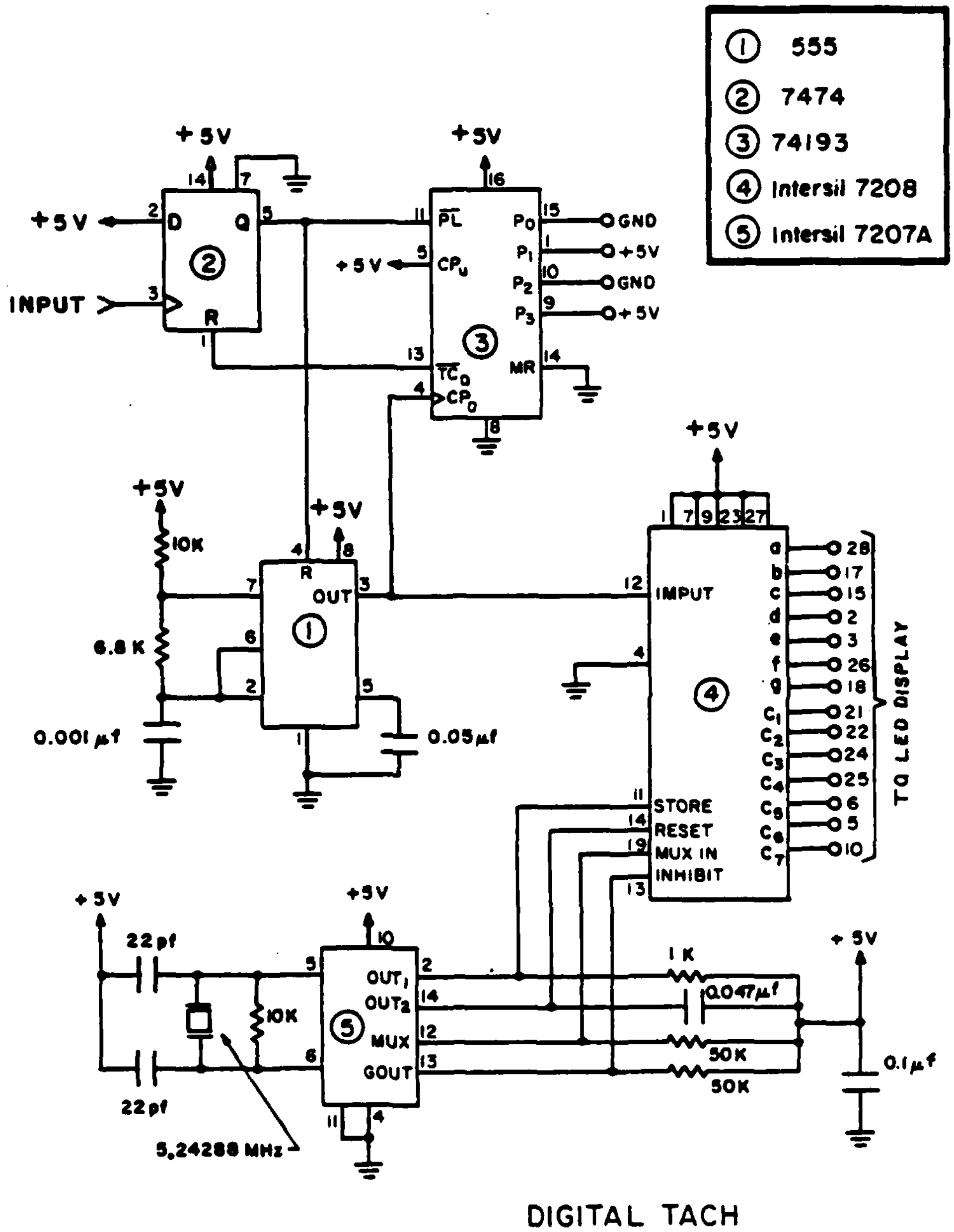
The 74193 counter, 7474 D-flip flop, and 555 timer make up the times-ten pulse multiplier. The flip flop output is normally low, holding the 555 timer in the reset mode, and forces the 74193 counter to load binary 1010, or 10 decimal. When a pulse appears at the 7474, its output goes high, allowing the 555 to oscillate, and the 74193 to count down from 10. When the 74193 reaches zero, it outputs a Terminal Count-Down (TCD) signal, which resets the flip-flop, halting the 555 and reloading the 74193 counter. This results in the 555 producing exactly ten pulses for each pulse received at the flip-flop.

The Intersil 7208 counts the pulses from the 555 for one second, latches the count, and provides multiplexed, seven-segment LED display drive signals. The Intersil 7207A is a crystal-controlled oscillator controller that provides timing for the 7208. At the end of each one-second interval, the INHIBIT signal appears, stopping the 7208 from counting. Next, the STORE signal causes the number in the 7208 counters to be latched, decoded, and displayed on the LED's. Finally, the RESET signal clears the counters, and the INHIBIT signal goes low, allowing the counting process for the next one-second interval.



BLOCK DIAGRAM - DIGITAL TACH

Figure 20.



① 555
② 7474
③ 74193
④ Intersil 7208
⑤ Intersil 7207A
INPUT
+5V
GND
TO LED DISPLAY
STORE
RESET
MUX IN
INHIBIT
10K
6.8 K
0.001 μf
0.05μf
22pf
1 K
0.047μf
50K
0.1μf
5.24288 MHz
DIGITAL TACH

Figure 21.

E. High Tension Transformer

Purpose

The transformer accepts the approximately 208 VAC-3ϕ output of the alternator, steps it up to two sections of 30 kvac and rectifies the power to produce about 125 kVp across the x-ray tube. The transformer assembly includes the current monitoring circuits and the filament transformer. When operating x-ray tubes at high potèntials, insulation requirements are reduced by dividing the voltage. At 120 kVp, the cathode will be operated at -60 kVp and the anode at +60 kVp.

Operation

Three-phase systems for 60 Hz operation are often made with the same high voltage rectifier circuit (3ϕ full-wave bridge) for each, or the two power circuits but with one transformer section wired delta and the other as Wye. This results in a 60° phase shift between the two sets of windings, a doubling of the effective ripple frequency and a reduction of the ripple voltage. For a resistive load, the ripple frequency will be 6 f for a Y-Y,Y configuration, and the ripple voltage will be about 8%. For the Y-Y, configuration, the ripple frequency will be 12 f and the ripple voltage about 3%. The secondary windings will have 3 e voltage across each where e is the terminal voltage to neutral so that the 12 f (or 12 pulse) transformer will require two different kinds of high voltage windings, while the 6 f (or 6 pulse) would use 6 identical coils.

At the higher frequencies of this system, 320 Hz rather than 60 Hz, the transformer can be made much smaller. The value of the ripple frequency for the 6 f circuit would be 1920 Hz (compared to 720 Hz for a 12 f - 60 Hz conventional "best" system). The tube cables have an electrical capacity of about 60 pf/ft and would be about 33 feet long in a typical field system; about 2000 pf each. The cable capacity should provide sufficient stored energy to smooth the "cusps" of the ripple voltage. If we assume the cables charge to some voltage and the "cusps" are 20% of each period (pulse to pulse), then the voltage drop will be less than:

$$\Delta V \leq i/6Cf$$

where C is the cable capacity and 6f is the ripple frequency. For a 250 mA exposure, $\Delta V \leq 6.9$ kV per cable. Thus, at these higher frequencies, 6f operation is a logical choice.

Design

The transformer itself was designed in the classical way [7], as Y-Y,Y using a 1.5 inch stack of magnetic metals 1.5EE3Ø, 6 mil grain oriented silicon steel laminations. Each of the three primary legs is wound on a paper tube and is 40 twin, trifilar, 18 AWG with a net resistance of 0.05 ohms max. Each of the six secondary coils is wound on a phenolic coil form and consists of 34 layers of 300 turns per layer (10,200 turns total) of 34 AWG with 10 to 12 mils of craft paper insulation per layer. The resistance of each winding is 3100 ohms typ. For an open circuit input voltage of 120 vac line to neutral, each secondary voltage will be 32 kvac for a rectified peak voltage of 3.2 k $10^4 x 3 \sqrt{2}$ or 125 kVp (entire assembly) or 68 kVp (each half). The high voltage coils were wound by Andover, Inc., of Lafayette, Indiana.

The rectifiers consist of silicon rectifier assemblies configured as six legs of 12 @ H463 Varo diodes for the anode and six legs for the cathode side. Metering diodes, filament transformer, terminals and cable sockets complete the unit. The transformer-rectifier assembly is then placed in a large polycarbonate tote box, filled with Shell Diala oil and vacuum pumped to eliminate air and moisture.

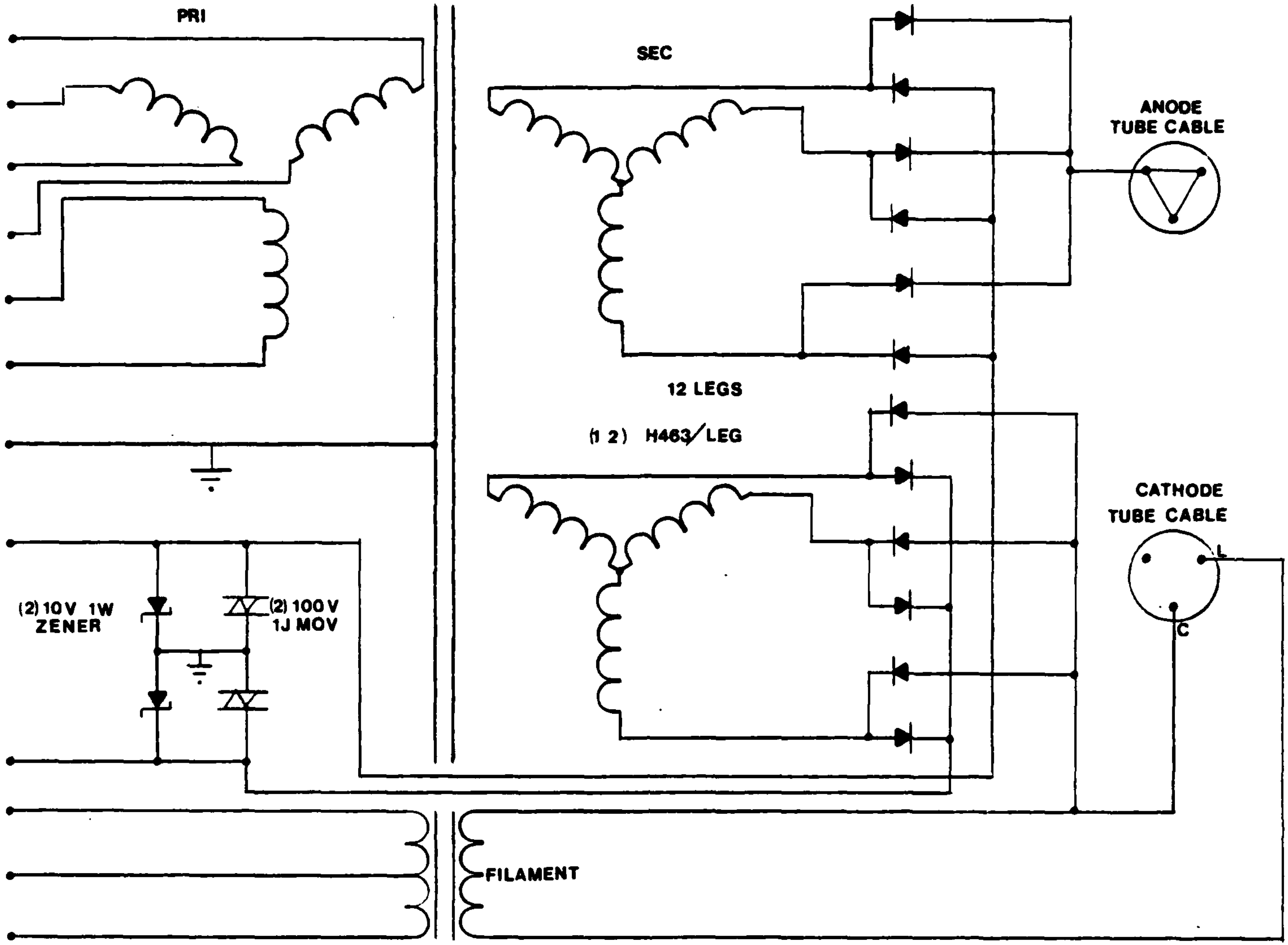


Figure 22. High Tension Transformer

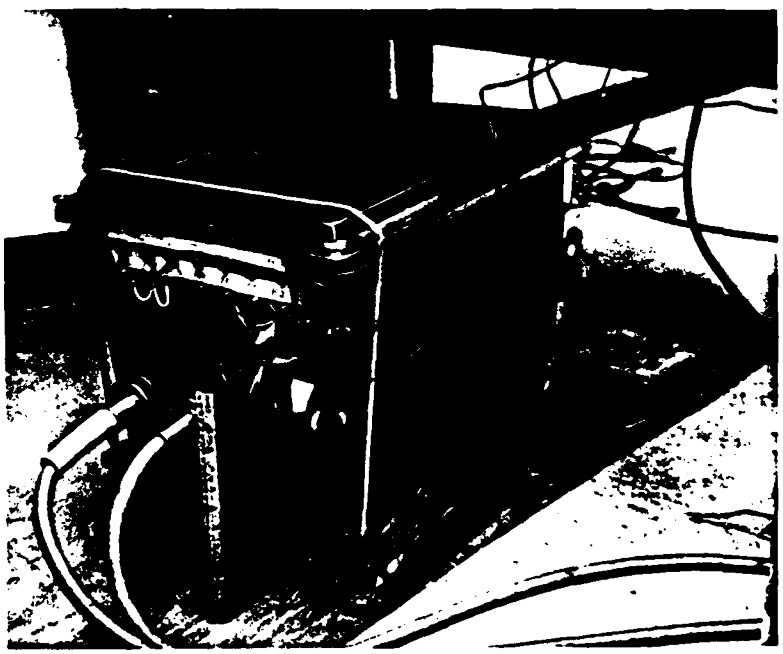


Figure 23. High Tension Transformer

F. Filament Circuit

Purpose

The filament circuit provides a constant current to the primary of the filament transformer. The filament transformer is located in the oil-filled high voltage tank and feeds the tube filament which is connected to the cathode side of the high tension transformer. The secondary is wound on a Delrin cylinder to insulate it for up to -75 kV from ground.

Operation

Potentiometers are set to different voltages corresponding to selected filament currents which will determine tube anode currents. The selector switch feeds the selected voltage through a 220K resistor to a summing amplifier. The voltage across a driver viewing resistor of 0.67 ohm and an external voltage proportional to anode voltage are also fed to the summing amplifier. Loop closure will hold the voltage across the viewing resistor perfectly proportional to the selected voltage minus a small compensation value for anode voltage.

The output of the summing amplifier is in rough proportion to the voltage at the viewing resistor and is the supply voltage to the CMOS driver, three sections of a quad two input nand gate. The nand gates accept the 200 Hz clock and convert it to push-pull signals of amplitude equal to the output of the summing amplifier. Those signals are fed to a pair of unity gain buffers, then to the bases of the driver transistors. The bases are also shunted by two transistors which will clamp the base signals to ground in the absence of the C_1 control signal. The collector current of the driver transistors feeds the primary of the filament transformer.

The filament transformer primary is wound as 48 turns C.T. of #20 copper wire on a Delrin tube 1.42 inch I.D., 1.58 inch O.D. and 3.0 inch long, over a one inch stack of Magnetic Metals C.I. 1.0 4 mil grain oriented steel. The secondary is wound in a Delrin tube 1.70 inch I.D., 2.25 inch O.D. and 3.0 inch long with 16 turns of #20 copper wire. For collector voltages of 84 V P-P maximum, the filament voltage is 14 V equivalent, and for primary currents of 4.0 amp average, the secondary current will be 6.0 amp.

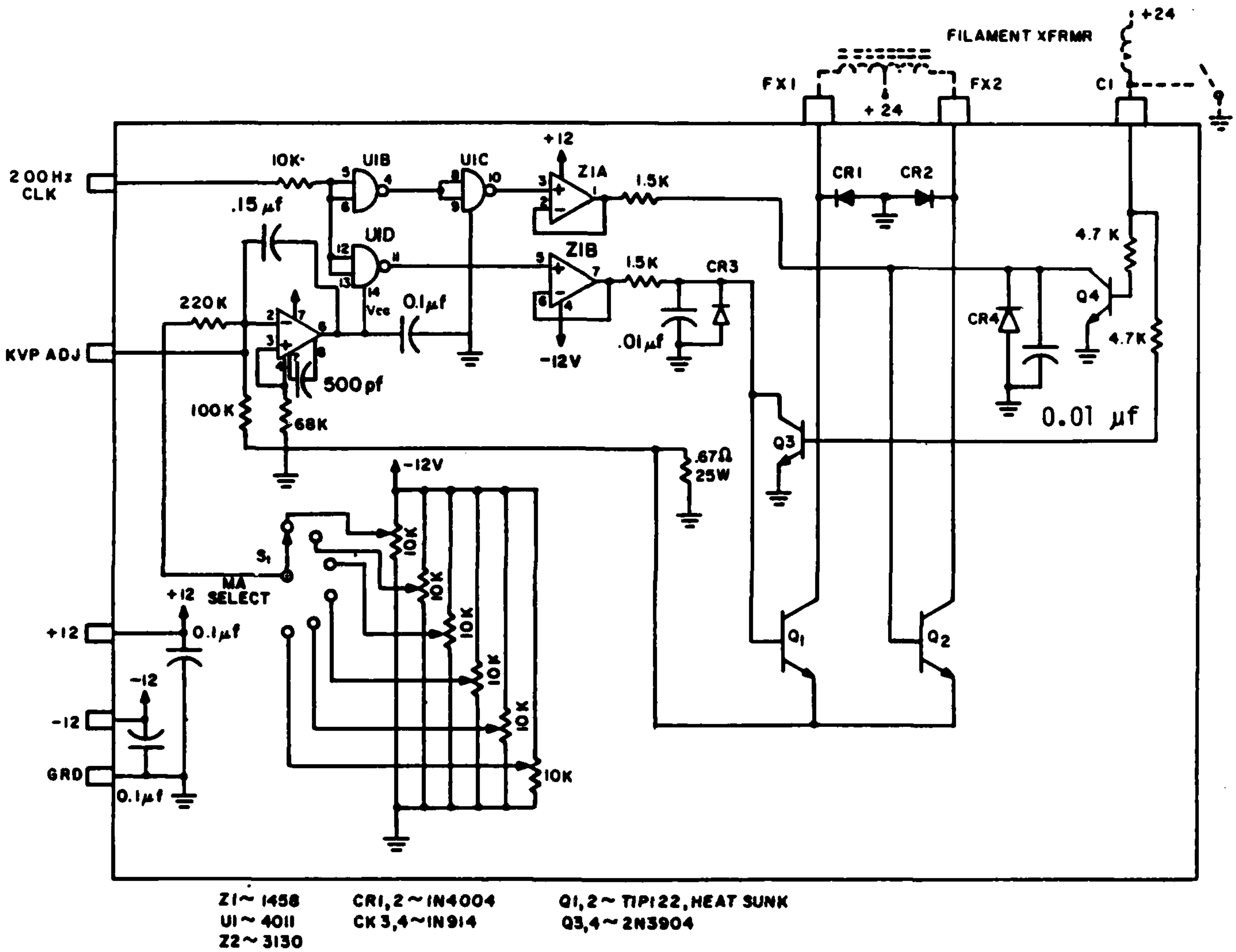

+24
FILAMENT XFRMR
FX1
FX2
C1
+ 24
+12
10K
U1B
U1C
Z1A
1.5K
CR1
CR2
200Hz
CLK
.15 μf
U1D
Z1B
1.5K
CR3
4.7 K
220K
0.1μf
Q4
CR4
KVP ADJ
Vcc
.01μf
4.7K
500pf
-12V
100K
68K
0.01 μf
Q3
-12V
.67Ω
25W
10K
S1
MA
SELECT
+12
+12
0.1μf
Q1
Q2
-12
-12
GRD
0.1μf
10K
Z1~ 1458
U1~ 4011
Z2~ 3130
CR1,2 ~ IN4004
CK 3,4 ~ IN914
Q1,2 ~ TIP122, HEAT SUNK
Q3,4 ~ 2N3904

Figure 24.

G. Tube Rotor Control

Purpose

This circuit provides power to the tube rotor. This is done at a high power level for fast start-up and a low power level for continued running. In addition, this circuit interlocks the exposure circuit. Exposure is not allowed unless the tube rotor is functioning and is up to the normal running speed.

Operation of Timer Circuits

Circuit timing performs two basic functions; ON/OFF control of the tube rotor and exposure control and timing between the fast start-up and normal running modes of power delivered to the tube rotor. Circuit timing is controlled by C1. When C1 is grounded, a nand gate of U2, as shown below, inverts the low input to a high of approximately 12 V which drives transistor Q1 into saturation.

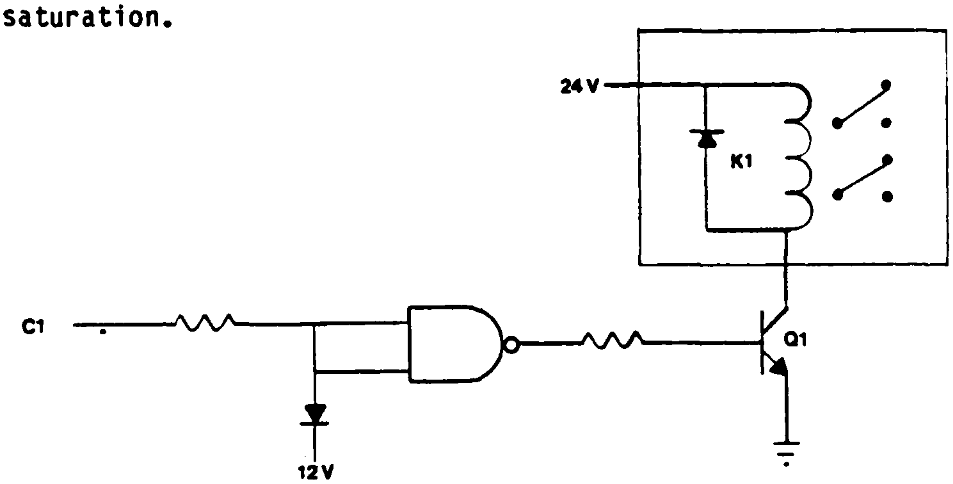


Figure 25.

When Q1 saturates, relay K1 closes causing the first of three exposure switches to close and Vcc to be supplied to the clock counter. In each case, neither an exposure nor power to the tube rotor is allowed if C1 is high.

A second function of circuit timing is to switch the power to the tube rotor from a high start-up level to a lower normal run level. This is done, pictured below, by a simple RC network.

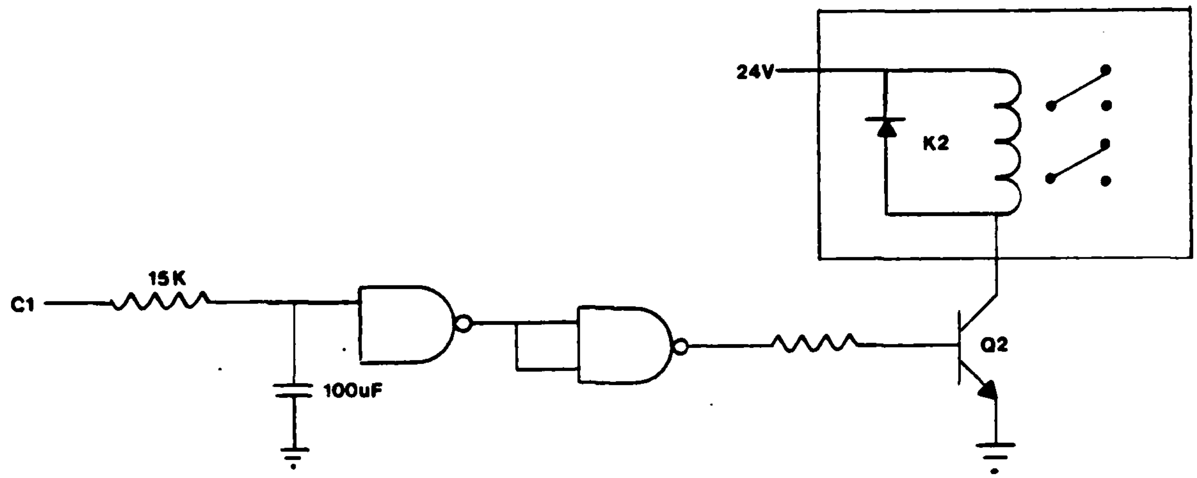


Figure 26.

As the inverted C1 makes its transition from 0V low to high, the resistor-capacitor delays the switching of the two nand gates by approximately 1.5 seconds. Once switched, the output of the second nand gate saturates transistor Q2, switching relay K2. Relay K2 energizes one of the two series Triacs, CR9 or CR10 to select high or low voltage from the inverter transformer to the rotor. Relay K2 also switches the closing of the second of three points which all must be closed to allow an exposure.

Tube Rotor Inverter

The tube rotor inverter consists of a transister-transformer assembly and supplies the two different output voltages.

The input 200 Hz clock is counted to provide the 50 Hz signal to drive the transistor pair, shown below.

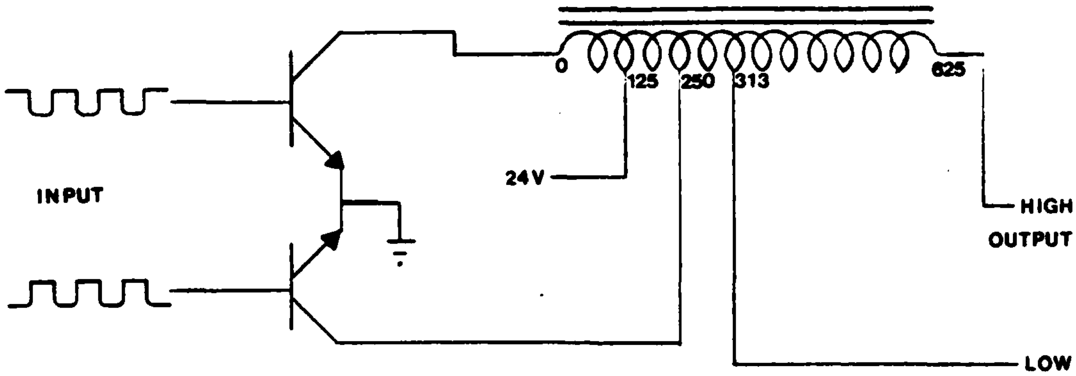


Figure 27.

The input signal alternately drives each collector to ground, drawing current through a leg of the transformer. The transformer, shown above, is a single winding of 625 turns, with taps of 125, 250, 313, 625. With 24 V at tap 125 and collectors at taps 0 and 250, each collector sees 48 V P-P. Output voltages at tap 313 (T1-B) are 72 V P-P and at tap 625 (T1-D) are 192 V P-P, biased at +24 VDC.

<u>Tube Rotor Monitor</u>

The operation of the tube monitor prevents an exposure in the case of tube rotor failure or an open wire. In normal operation, activation of C1 closes the first of three relays which activate the exposure control. After approximately one second, a second exposure control relay is closed, meaning the tube rotor is up to speed. The function of the tube monitor is to check if power is being delivered to the tube rotor and, if so, to close the third set of contacts in series with the exposure control switch. The circuit for the tube monitor is shown below.

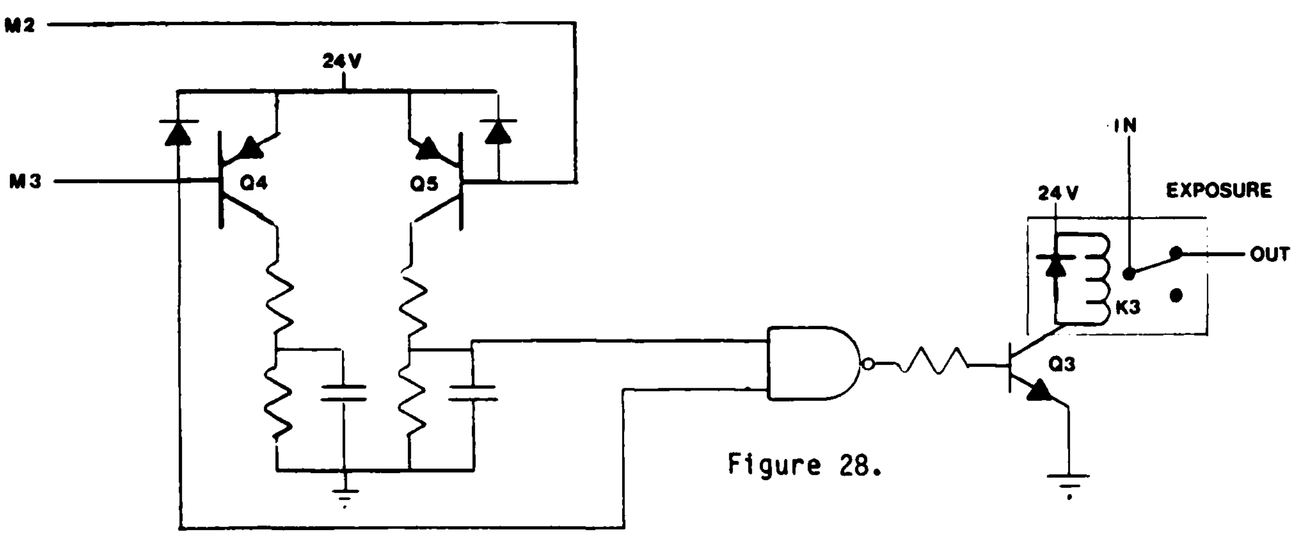
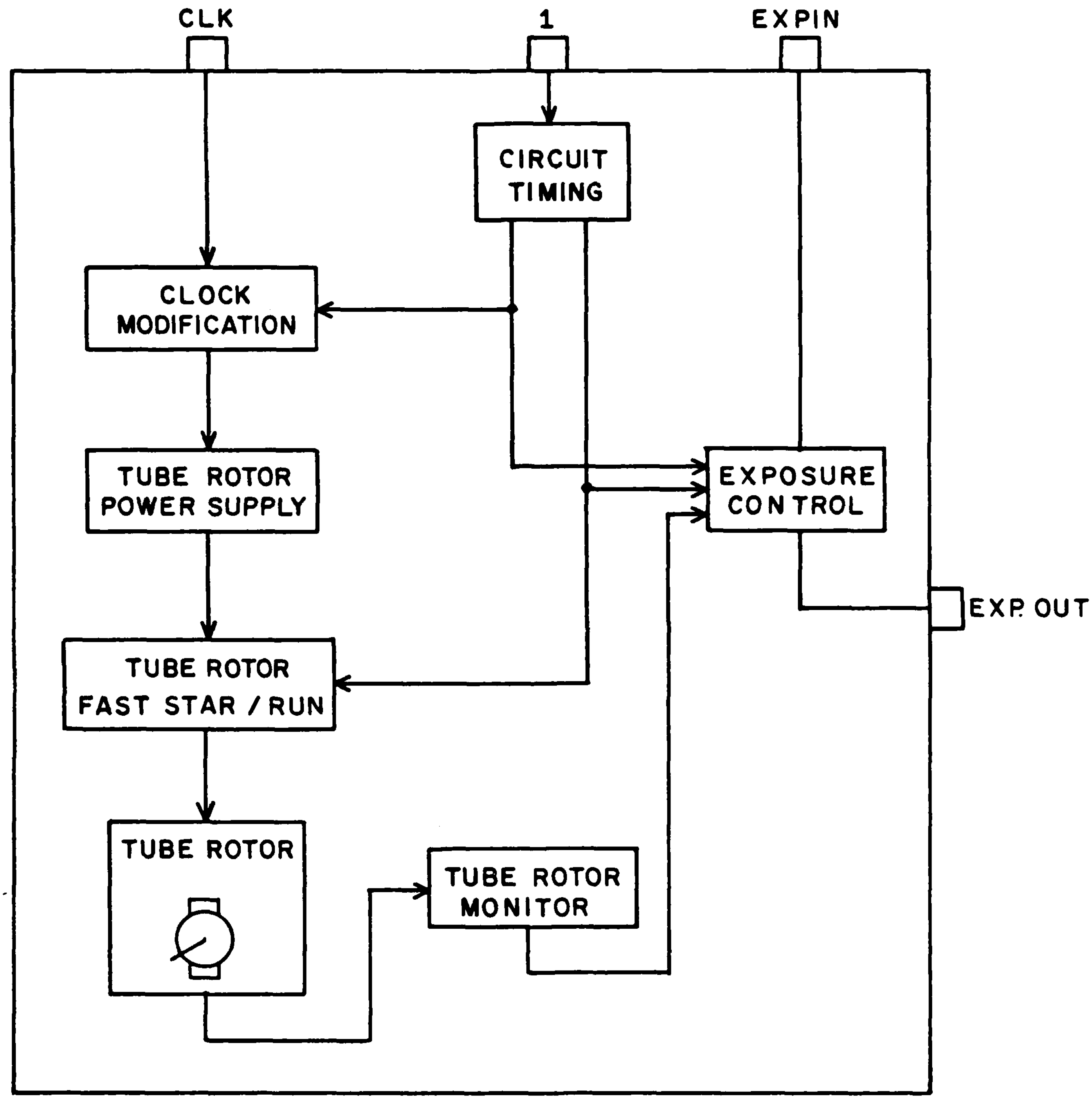


Figure 28.

Current is fed to the tube rotor through M1 and returned by M2 and M3. The 22 uf rotor phase shift capacitor is in series with M2. Because the voltage fed to the rotor coils is biased at +24 VDC, M2 and M3 are returned to +24 via a diode (positive 1/2 cycles) and the base-emitter diode equivalents of two power transistors. If current is flowing in both rotor coils, both Q4 and Q5 will be saturated 50% of the time 50 times per second, and the two 10 uf capacitors in their collector circuits will be held at between +12 and +16 VDC, sufficiently high to be used as inputs to one of the four nand gates of V2 and hold its output low. That low output holds off Q3, and the N.C. contacts of relay K3 are part of the exposure interlock. Loss of current in either rotor coil will energize K3 and prevent exposure and save the tube.

Conclusion

The tube rotor control has the function of preparing the anode of the x-ray tube for an exposure. These preparation steps performed include an ON/OFF control by C1, a high-powered, fast start-up and an exposure control preventing an exposure if not all of these requirements are met.



BLOCK DIAGRAM TUBE ROTOR CONTROL

Figure 29.

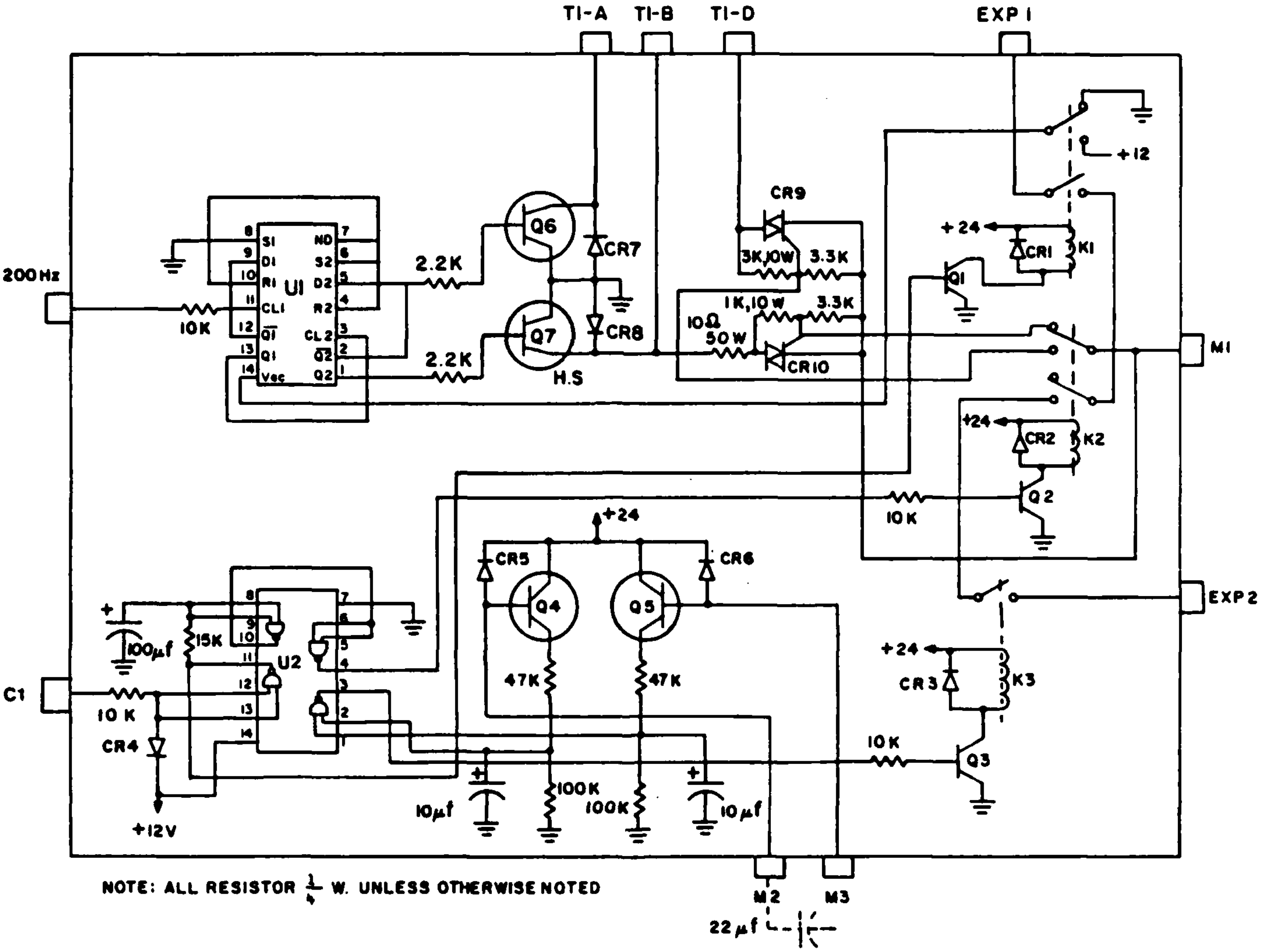

TI-A
TI-B
TI-D
EXP I
+12
CR9
+24
CRI
KI
3K,IOW
3.3K
Q6
CR7
2.2K
200Hz
UI
IOK
QI
IK,IOW
3.3K
IOΩ
50W
Q7
CR8
2.2K
H.S
CRIO
MI
+24
CR2
K2
Q2
IOK
+24
CR5
CR6
Q4
Q5
EXP2
100μf
15K
U2
+24
CR3
K3
47K
47K
CI
IOK
CR4
IOK
Q3
IOμf
IOOK
IOOK
IOμf
+12V
NOTE: ALL RESISTOR 1/4 W. UNLESS OTHERWISE NOTED
M2
M3
22μf

Figure 30.

H. Field Current Controller

Purpose

The purpose of the Field Current Controller is to provide current to the exciter of the alternator. The motor-generator operates in two modes, the motor mode and the alternator mode. During the motor mode, the controller provides 20 mA of current to the exciter to increase the stator to rotor coupling without creating excessive back emf. During an exposure, the C_2 line goes low causing a shift from the motor mode to the alternator mode. In this mode, the controller increases the exciter current to the value set with the kVp select potentiometer on the front panel. When commanded by the timer module, the controller also boosts the current to a higher value to compensate for the output sag due to a heavy load.

It had been observed that the rate of change of voltage, the voltage sag, during pulse testing was about that expected for an L/R time constant where L is the inductance of the field and R is the shunt resistance due to eddy currents and other losses. A boost pulse, a flat increment of field current, can be set to just compensate for that sag.

The current controller also provides a voltage signal proportional to the exciter current which is used by the relay controller to protect the drive current from excessive back emf.

Operation

The current is controlled using a viewing resistor voltage as feedback to a differential amplifier which compares the value to a reference voltage. The differential amplifier drives a Darlington transistor which controls the current in the exciter. The block diagram shows the operation of the controller. V_{ref} is produced by summing and amplifying the voltages from the various select points when enabled by C_2. When disabled, the voltages are zero.

The complete wiring schematic follows. A clamping diode across the exciter limits switching spikes to about 24 volts. Additional protection is provided by limiting V_{ref} with a voltage divider at the input to the differential amplifier driving the transistor. This limits the exciter current to about 2.5 amps. Finally, the signal from the timer is a pulse which is detected by the 4027 which is a J-K flip-flop. The output switches a solid state relay, 4066, which adds the boost signal to the sum point. The signal is switched off when C_2 goes high and the flip-flop is reset.

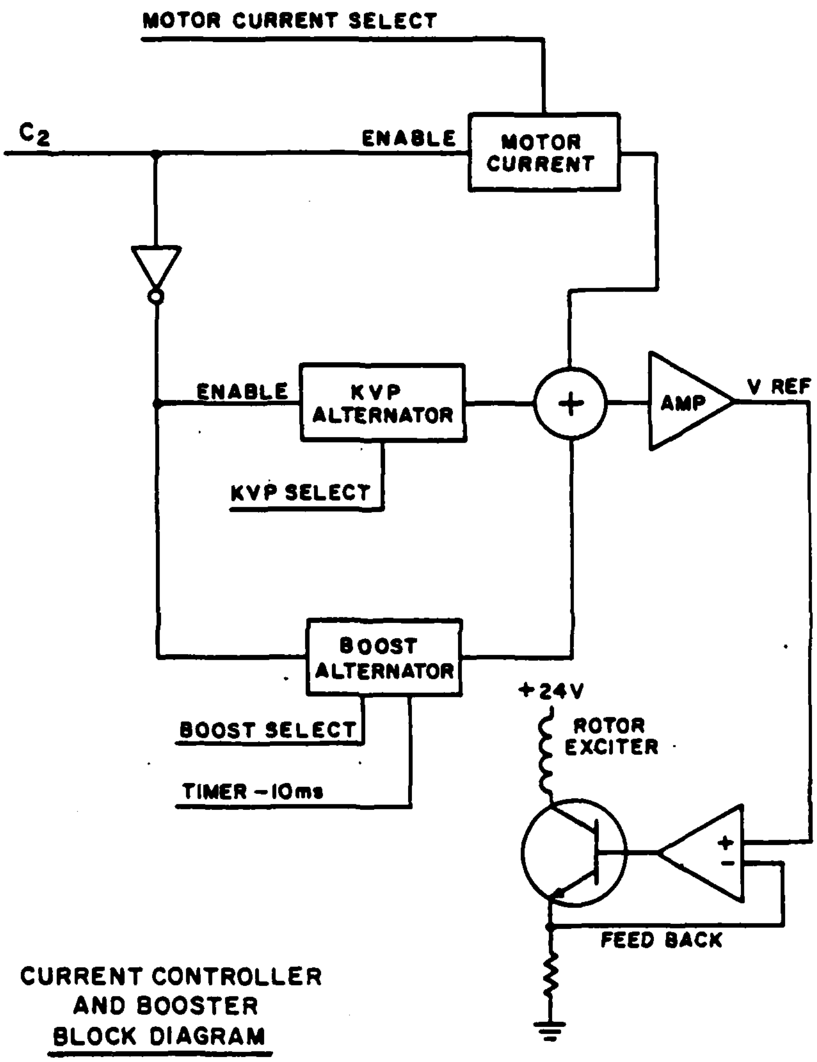
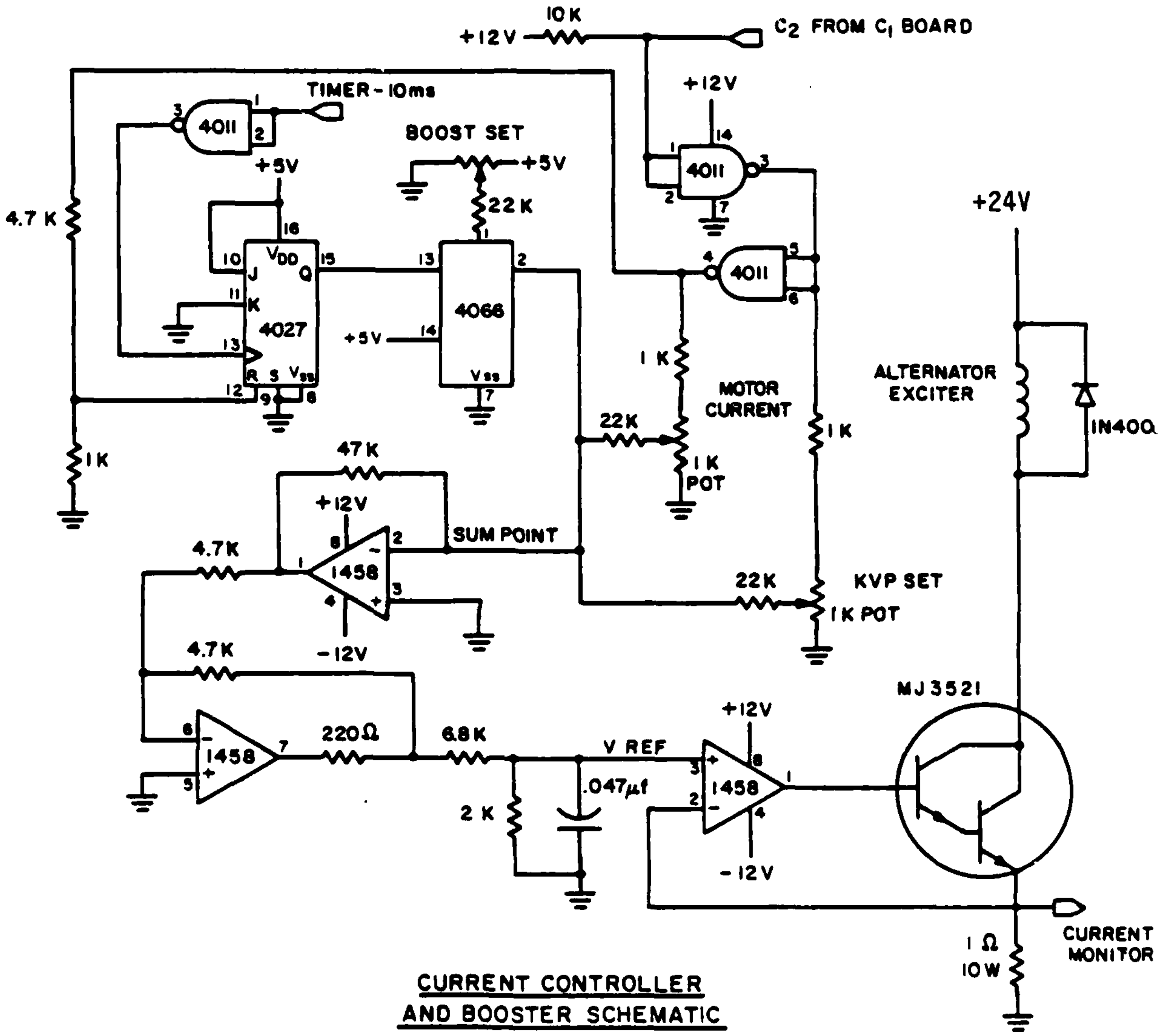

MOTOR CURRENT SELECT
C2
ENABLE
MOTOR CURRENT
ENABLE
KVP ALTERNATOR
KVP SELECT
AMP
V REF
BOOST ALTERNATOR
BOOST SELECT
TIMER -10ms
+24V
ROTOR EXCITER
FEED BACK
CURRENT CONTROLLER
AND BOOSTER
BLOCK DIAGRAM

Figure 31.



CURRENT CONTROLLER
AND BOOSTER SCHEMATIC

Figure 32.

I. Exposure Timer

Purpose

When the operator of the x-ray machine closes the switch (C2) to make an exposure, two things must happen. First, there must be a delay before connecting the alternator to the high tension transformer to allow time for a rotor current boost. This boost is a ramp of current from the rotor current boost controller, which must receive a voltage step before the alternator is connected to the high tension transformer. Second, the alternator must remain connected to the high tension transformer for a specified exposure time.

Description

100 ms delay. When C2 is closed, a capacitor, that was initially charged to +12V, discharges to ground through a resistor (10K). The voltage on the capacitor (a decaying exponential) is compared to a reference voltage (between 0 and +12 volts) by a comparator (CA3130) which gives an output of 0 volts when the voltage on the capacitor is less than the reference voltage. This output of 0 volts occurs approximately 100 m sec after C2 closes. The output of the comparator generates a negative-going spike by dumping the capacitor in the following circuit to ground through the diode.

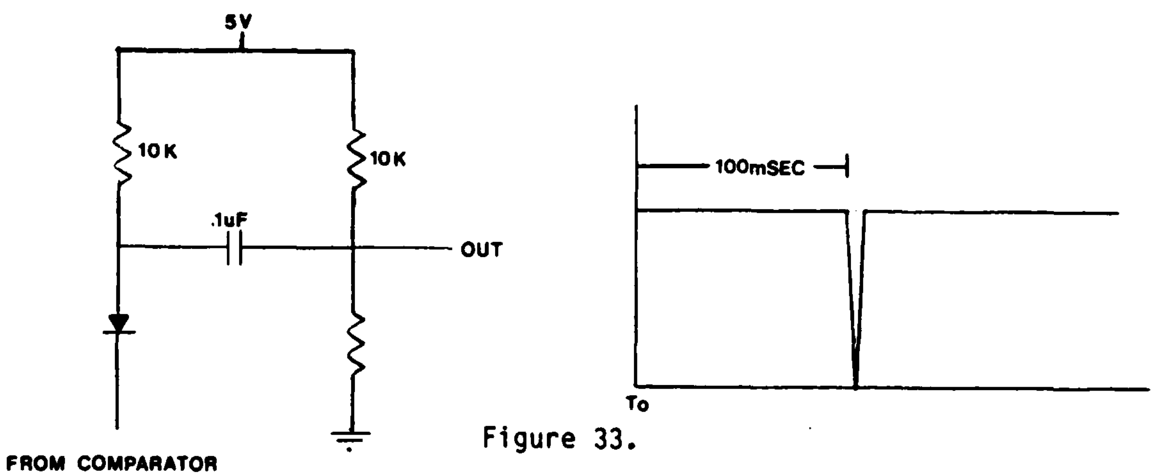
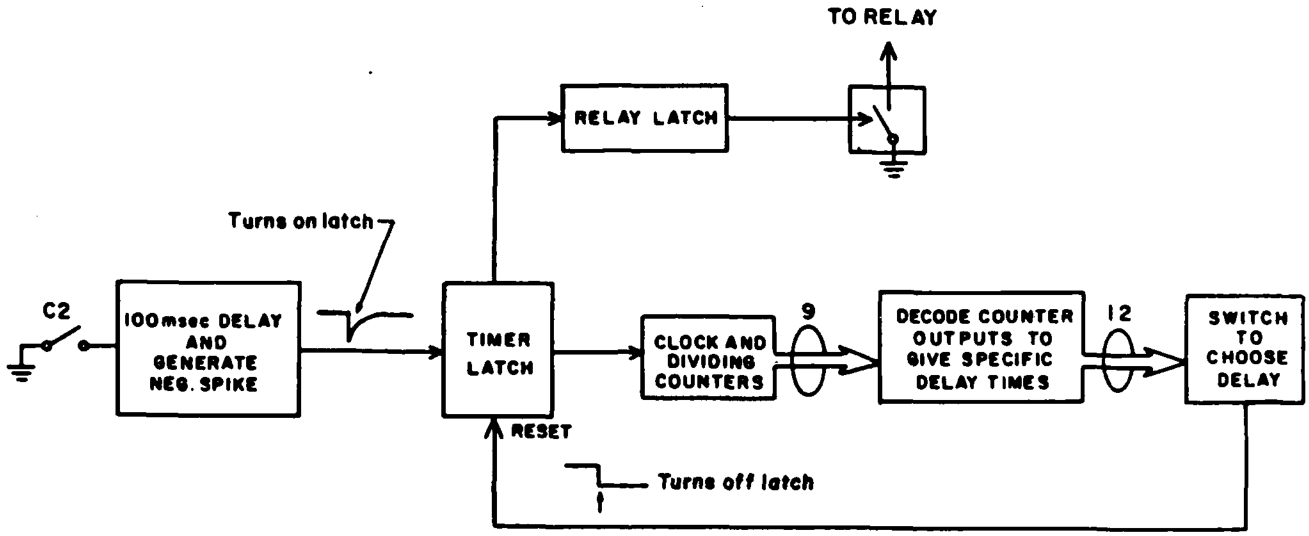


Figure 33.

The "spike" sets the timer latch to have a positive output. The timer latch remains set (high) until it is reset by S1 going low at the end of the exposure time. The high output from the timer latch connects the 200 Hz clock to the dividing counters. The counter outputs are decoded by 12 nand gates to give delays of 0.01, 0.02, 0.03, 0.05, 0.07, 0.10, 0.15, 0.25, 0.35, 0.50, 0.70, and 1.0 seconds.

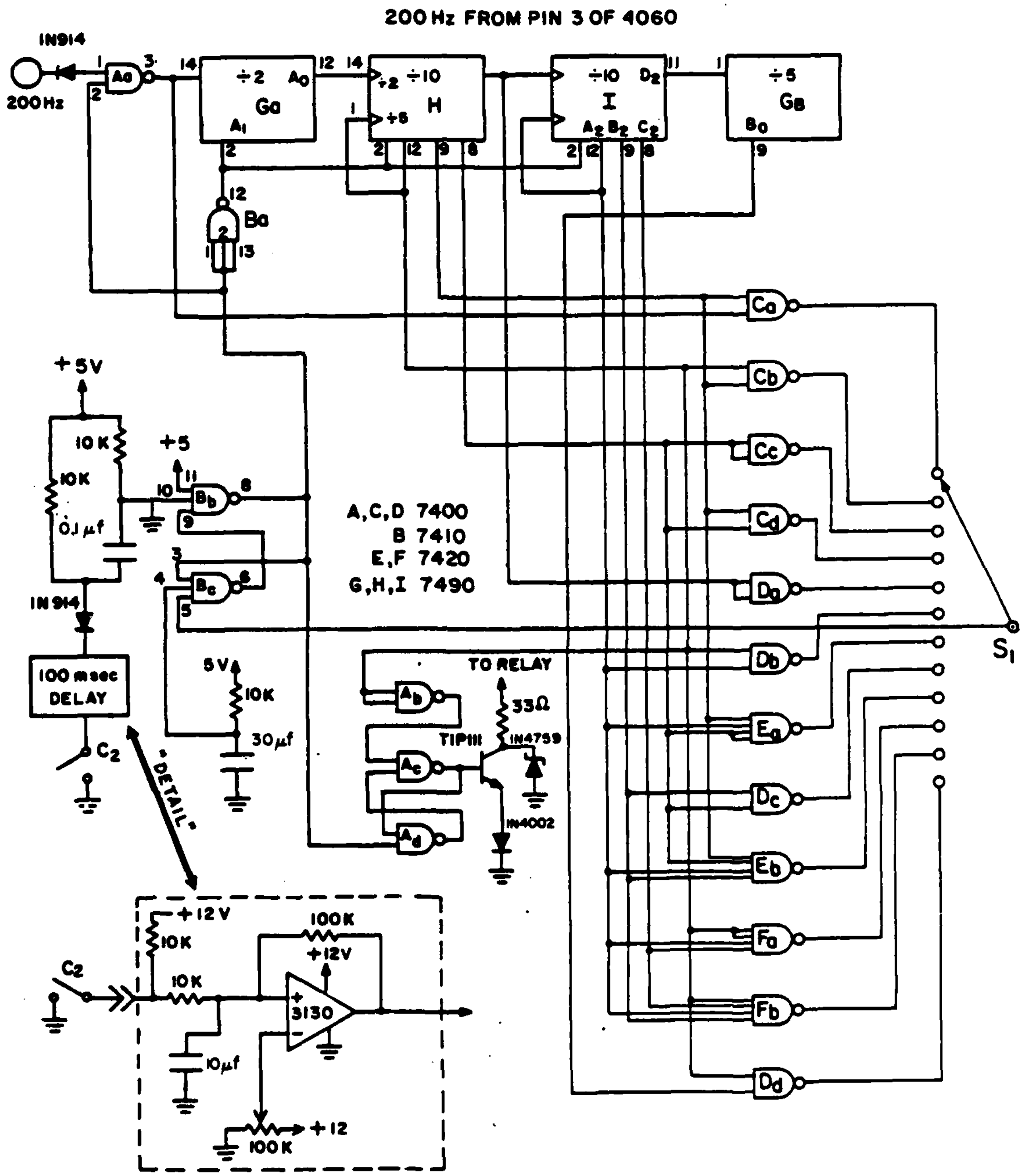
The outputs of the nand gates are normally high, but when the selected delay has elapsed that output goes low. The "exposure time" switch is a rotary switch which connects the output of the appropriate delay to the RESET input (S1) of the timer latch. Therefore, after the appropriate delay, the timer latch is reset and the clock is disconnected from the counters. The counters are set to 0 at pin 2 of 7490 when the latch is reset. This leaves them in an initialized state for the next exposure.

The output of the timer latch, when set, also sets the relay latch after the first count of the ÷2 counter. The relay latch remains set until the timer latch is reset. Therefore, the relay latch remains set for the full exposure time. The output of the relay latch drives the base of a TIP 111 transistor. When the relay latch is high, the TIP 111 turns on and the relay is tripped. The relay opens when the TIP 111 turns off due to a low output on the relay latch.



EXPOSURE TIMER

Figure 34.



200 Hz FROM PIN 3 OF 4060
IN914
200Hz
÷2
Ga
÷10
H
÷10
I
÷5
GB
A,C,D 7400
B 7410
E,F 7420
G,H,I 7490
+5V
10K
0.1 μf
100 msec DELAY
C2
"DETAIL"
5V
30μf
TO RELAY
33Ω
TIP111
IN4759
IN4002
S1
+12V
100K
3130
10μf
+12

Figure 35.

J. Controlled Output Testing

The system was subjected to two series of tests to establish output control. The first series consisted of a series of low power exposures, 1 to 12 kW. During these tests, the step increase in the exciter current at the time of exposure was determined, which corrected the voltage sag observed in the output under light lods. The second series of tests were in the 15 to 25 kW range. These tests were run using resistive loads to protect the transformer and tube but the purpose remained the same, to determine the step increase in the exciter current necessary to give constant kVp output during the pulse loading.

Low Power Tests

During low power exposures, there are two sources of power:

(1) The energy stored in the stator windings developed during open circuit voltage operation just prior to the exposure.

(2) Power moved across the air gap due to the cutting of the flux between the rotor and stator.

During an exposure, the stored energy provides power at a rate determined from the loading and a sag in the output is observed. To compensate for this sag, the exciter current is increased at the time of exposure. It was established during early testing of the alternator that the system response, the sagging and exciter response, were nearly equal, and thus a step increase in the exciter current offered a control strategy.

Procedure

The flywheel motor-generator system was run at 9500 and 9000 rpm. At each speed, the initial exciter current was set at a level corresponding to 80 kp at the beginning of the exposure as measured using a voltage divider.

Loads were adjusted using the filament voltage (mA). Coincident with an exposure, the exciter current was boosted to a level which was observed to have produced a constant output. The boost level was recorded together with the mA, mAs, mR, filament voltage, initial exciter current, and flywheel speed. The data is present in the Table 6.

Table 6

Output Control Data

RPM	V_{fil}	mR	mAs	I_{ex} (Initial)	I_{ex} (Final)	Time(s)	kVp
9500	12.0	48	6	.5	.7	.140	80
9500	13.0	88	10	.5	1.0	.140	80
9500	12.5	73	8	.5	.9	.140	82
9500	13.5	123	14	.5	1.3	.140	80
9500	14.0	174	18	.5	1.6	.140	82
9500	11.5	35	4	.5	.6	.140	80
9500	11.0	22	2	.5	.55	.140	78
9000	11.0	34	2	.55	.65	.140	80
9000	12.0	55	6	.55	.80	.140	80
9000	13.0	92	11	.55	1.10	.140	80
9000	12.5	71	8	.55	.90	.140	84
9000	13.5	116	14	.55	1.30	.140	80
9000	14.0	155	18	.55	1.60	.140	82

Analysis

Analysis of the data revealed a linear relationship between the required boost current, $I_{final} - I_{initial}$ and the mA. This relation is seen in a plot of the data in Figure 36.

Two photos are seen in Figure 37. The first is at 128 mA; the second is at 7 mA. The first required a boost of 1.1 ampere while the second exposure required no boost to sustain the output level.

The results indicate that a control strategy at 80 kVp may be estimated in the 8500 to 9500 rpm range by:

$$\text{Initial} \approx \frac{.1A}{\text{krpm}} (\text{speed (krpm)}) - .95A$$

and
$$I_{Boost} = I_{final} - I_{initial} = \frac{1A}{100\ \mu A}(\mu A) - .2A$$
$$20\ mA \leq mA \leq 130\ mA$$
$$I_{Boost} = 0 \qquad 0 \leq mA < 20\ mA$$

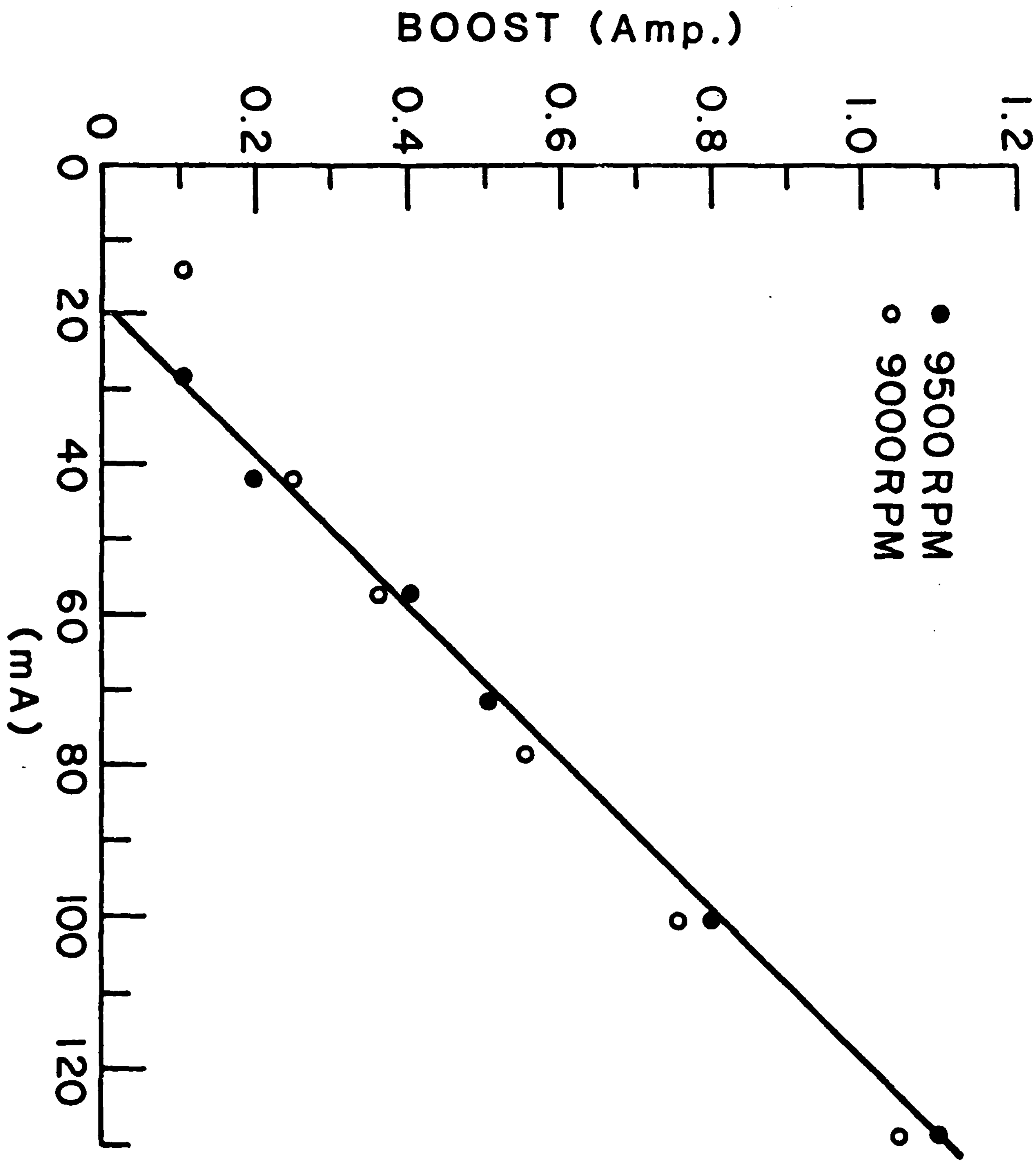
High Output Testing

At high output levels, the boost currents dominate the initial current used to set the open circuit voltage. The response times are shorter. It has been found that a low initial current level is required and only the boost level need be used to set the output with little voltage sag observed. The high output tests were done using resistive loads to reduce the risk of system damage at high output levels. Data was taken at 9000 rpm with 1 ohm/leg Wye load. Power levels were set at 15 kW and 24 kW. Boost levels of 1.6A and 1.8A were used to give the sought output photos of the waveforms appear in Figure 38.

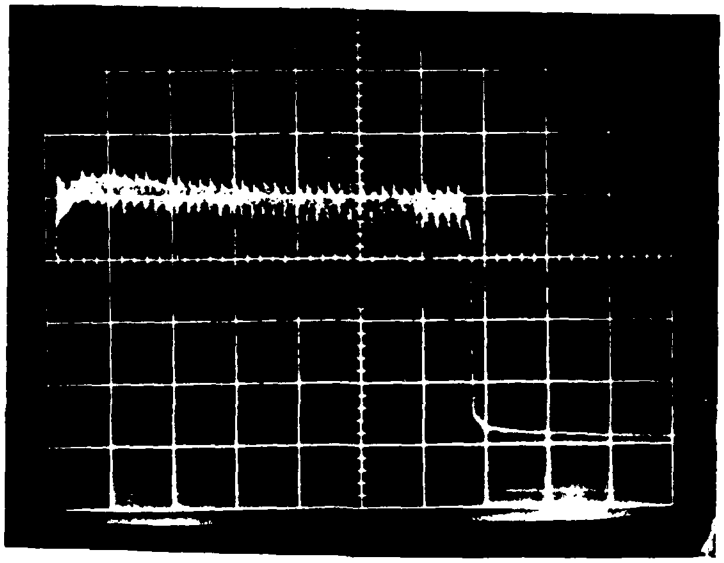
Summary

The tests indicated that the combinations of open circuit voltage and boost at exposure was sufficient to control the output to within 3% of the target value at low power levels while at high output, the boost current is sufficient for control. The boost current at low power levels appears to be a linear function of mA.

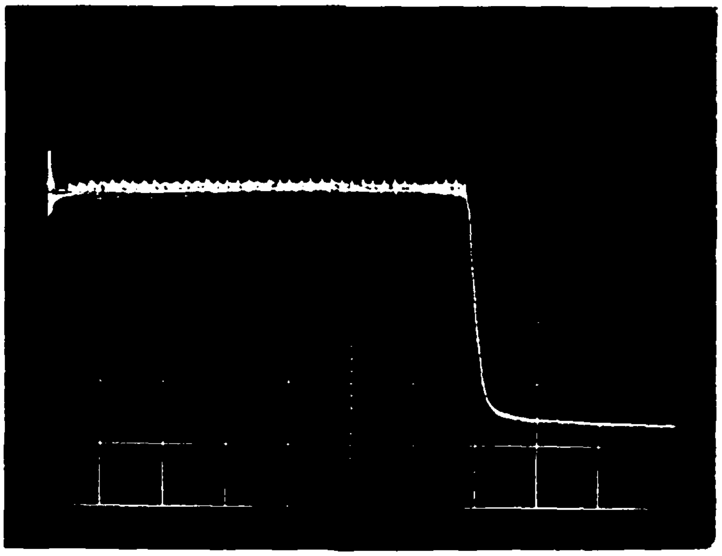
Figure 36



BOOST (Amp.)
0
0.2
0.4
0.6
0.8
1.0
1.2
0
20
40
60
80
100
120
(mA)
9500RPM
9000RPM

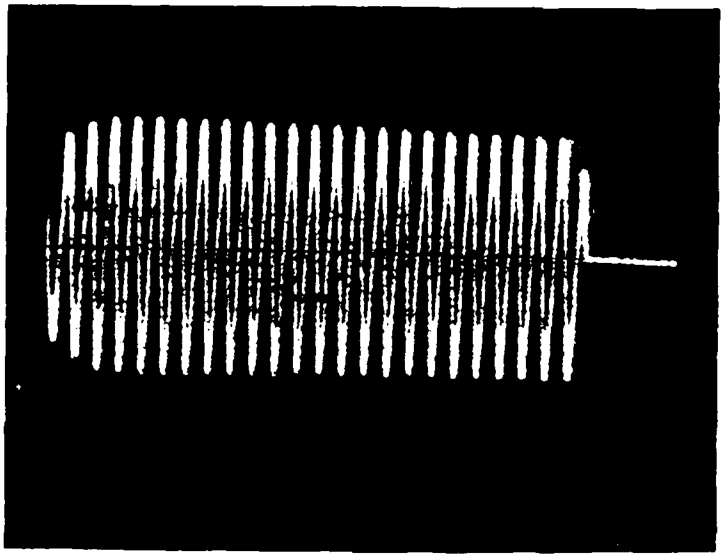


128 mA

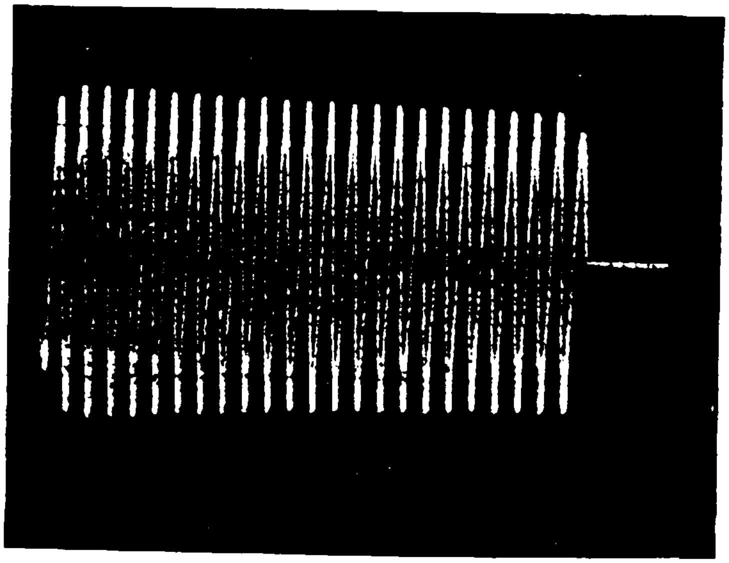


7 mA

Figure 37. Photos of output taken during low power testing. Anode waveforms, 10 kV/Div, V_{ert}, 20 ms/Div, Hor.



1.6 A Boost



1.8 A Boost

Figure 38. Photographs of waveforms in resistive load tests.
50 volt/Div, V_{ert}, 10 ms/Div, Hor.

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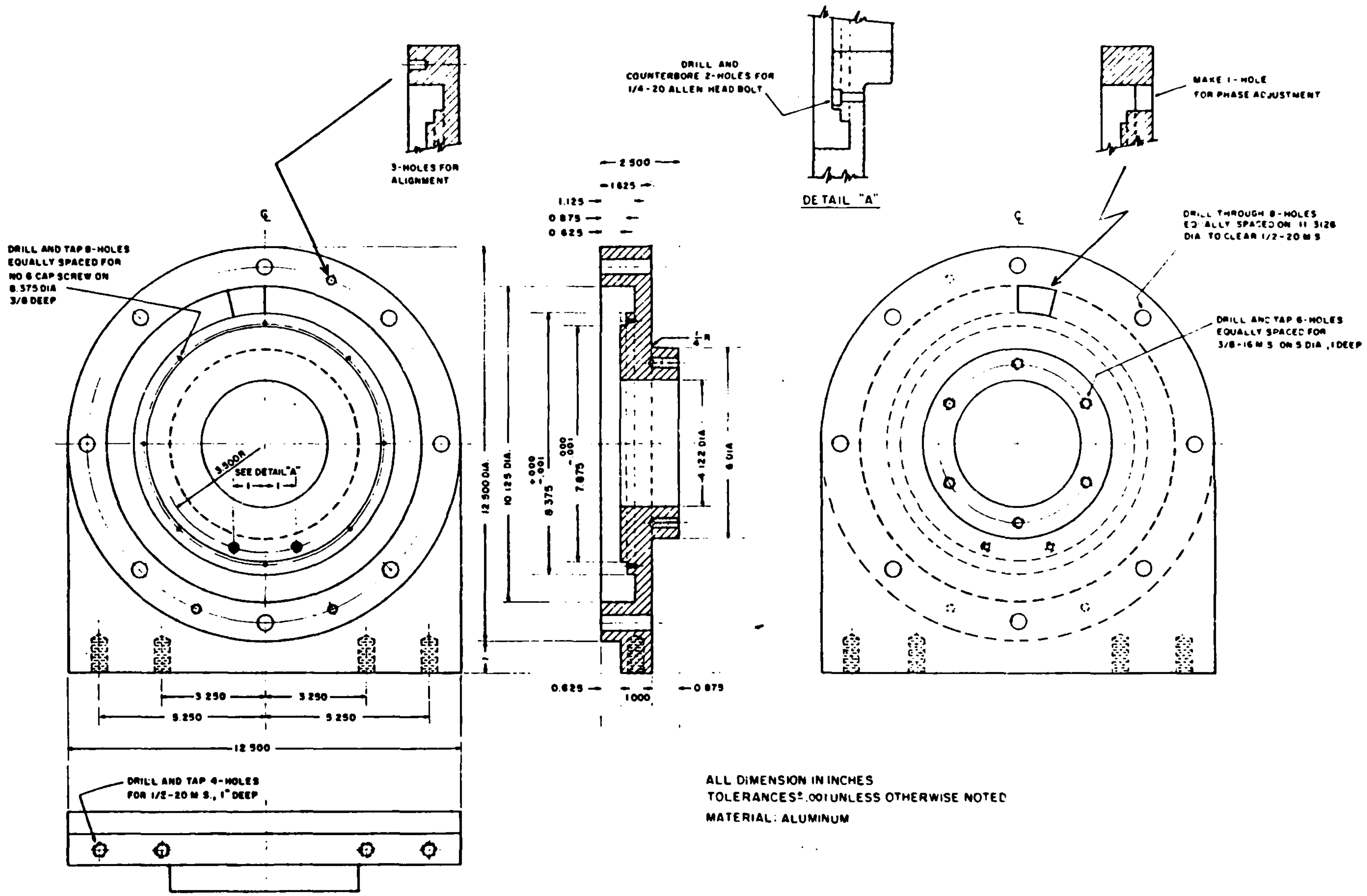
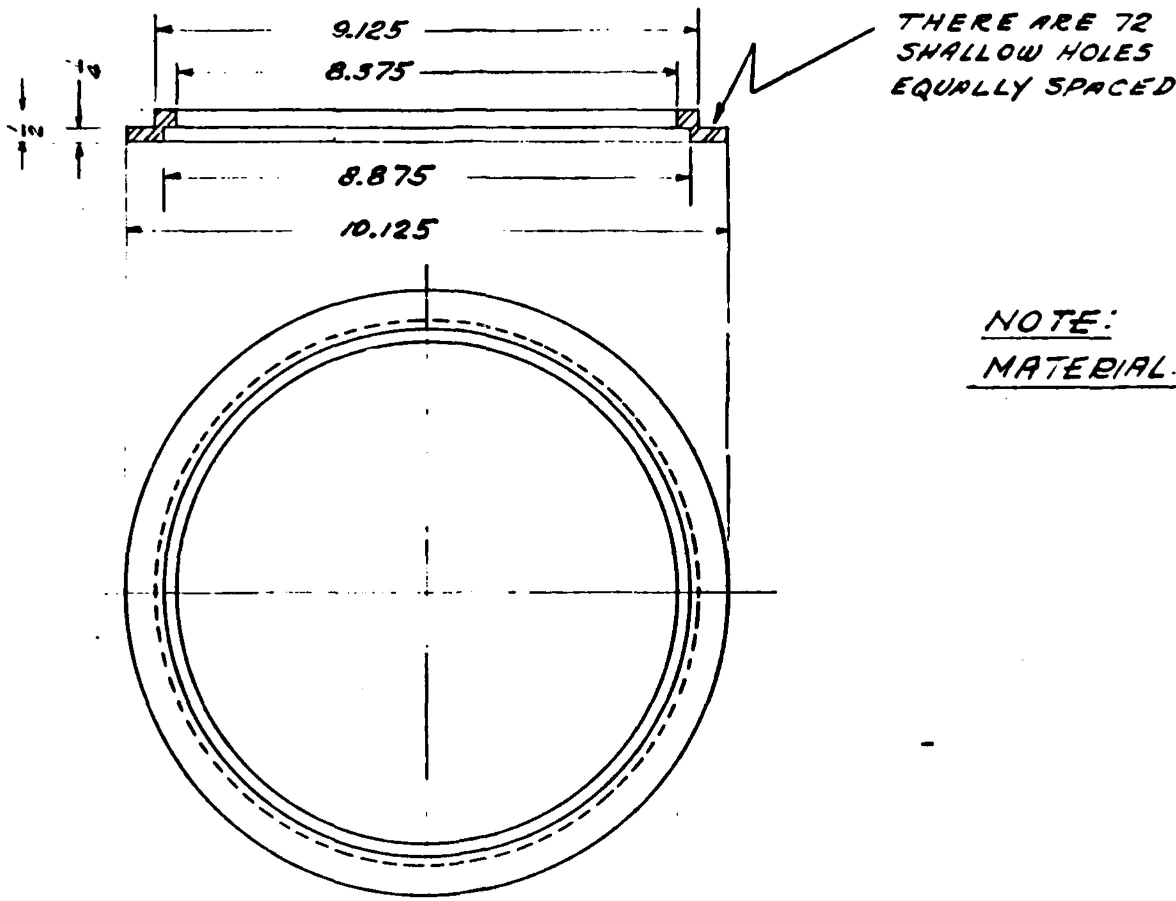


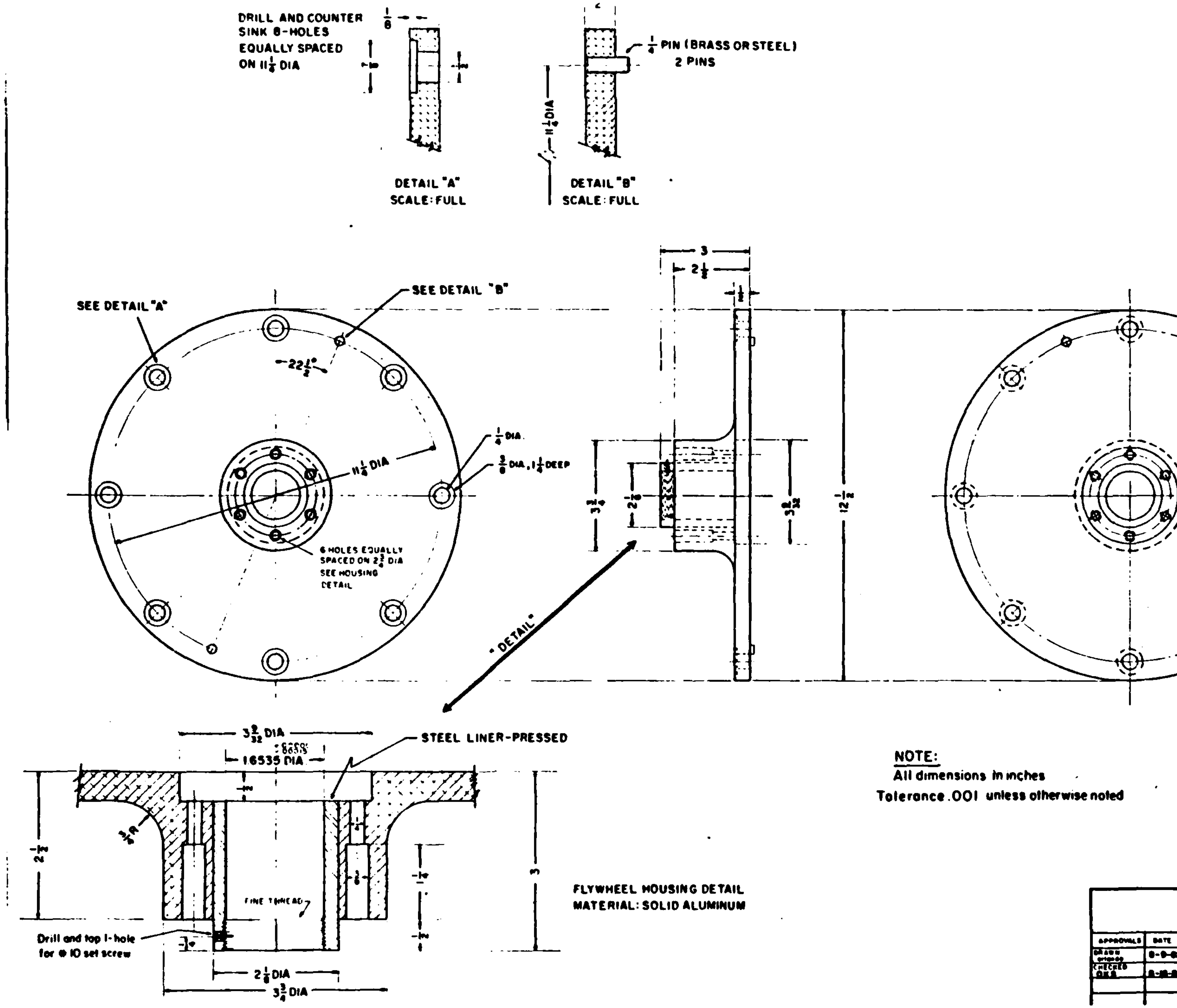
ALL DIMENSION IN INCHES
TOLERANCES ±.001 UNLESS OTHERWISE NOTED
MATERIAL: ALUMINUM

UNIVERSITY OF WISCONSIN		
M-G MOUNT (Flywheel		
Scale 1/2:1	Drawn Orlando	Checked
Drawing No		1-18-83



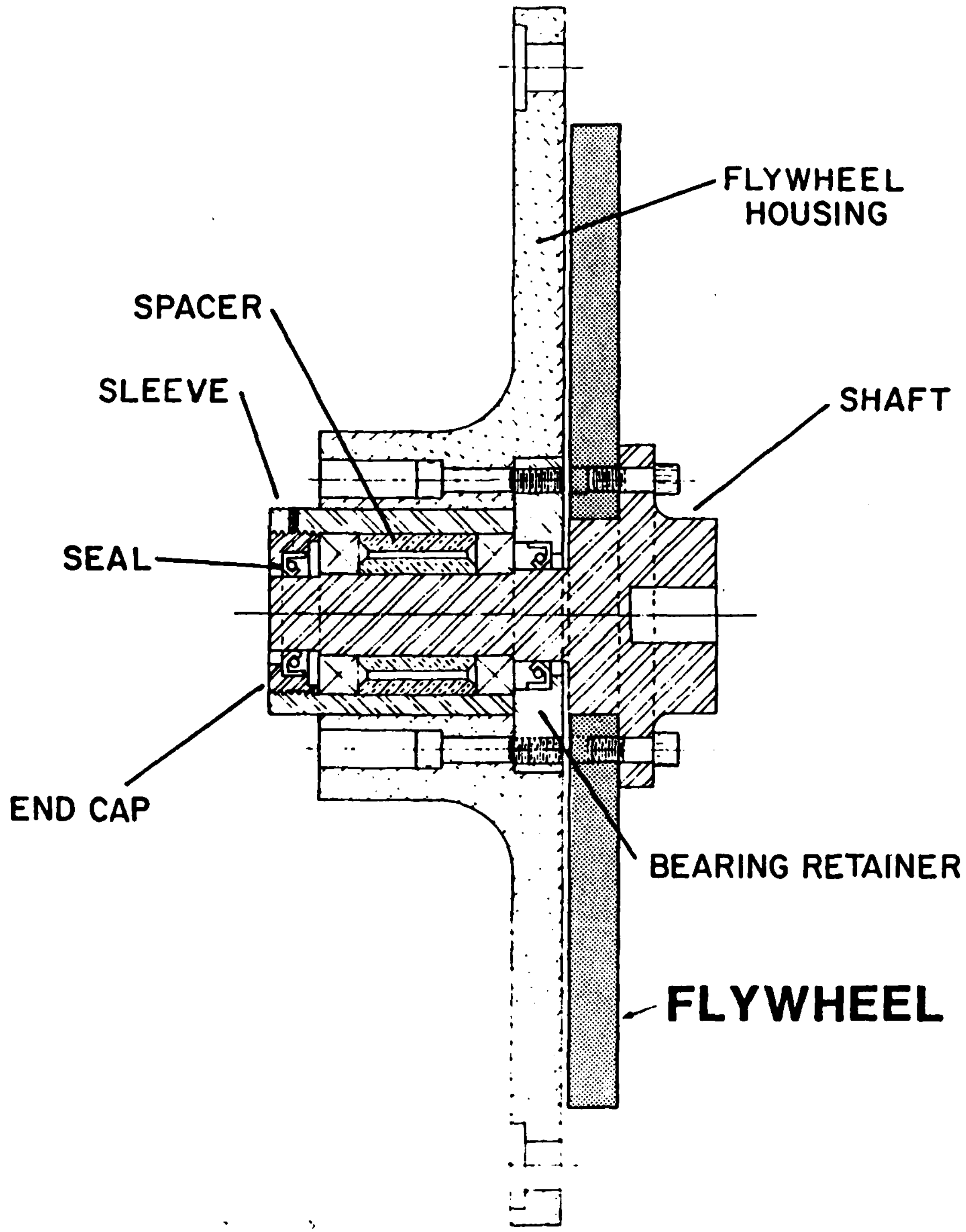
NOTE:
MATERIAL. ALUMINUN

UNIVERSITY OF WISCONSIN		
TITLE TRANSDUCER RING		
SCALE $\frac{1}{2}$:1	DRAWN ORLANDO	DRAWING NO
CHECKED	APPROVED	DATE 10-19-82

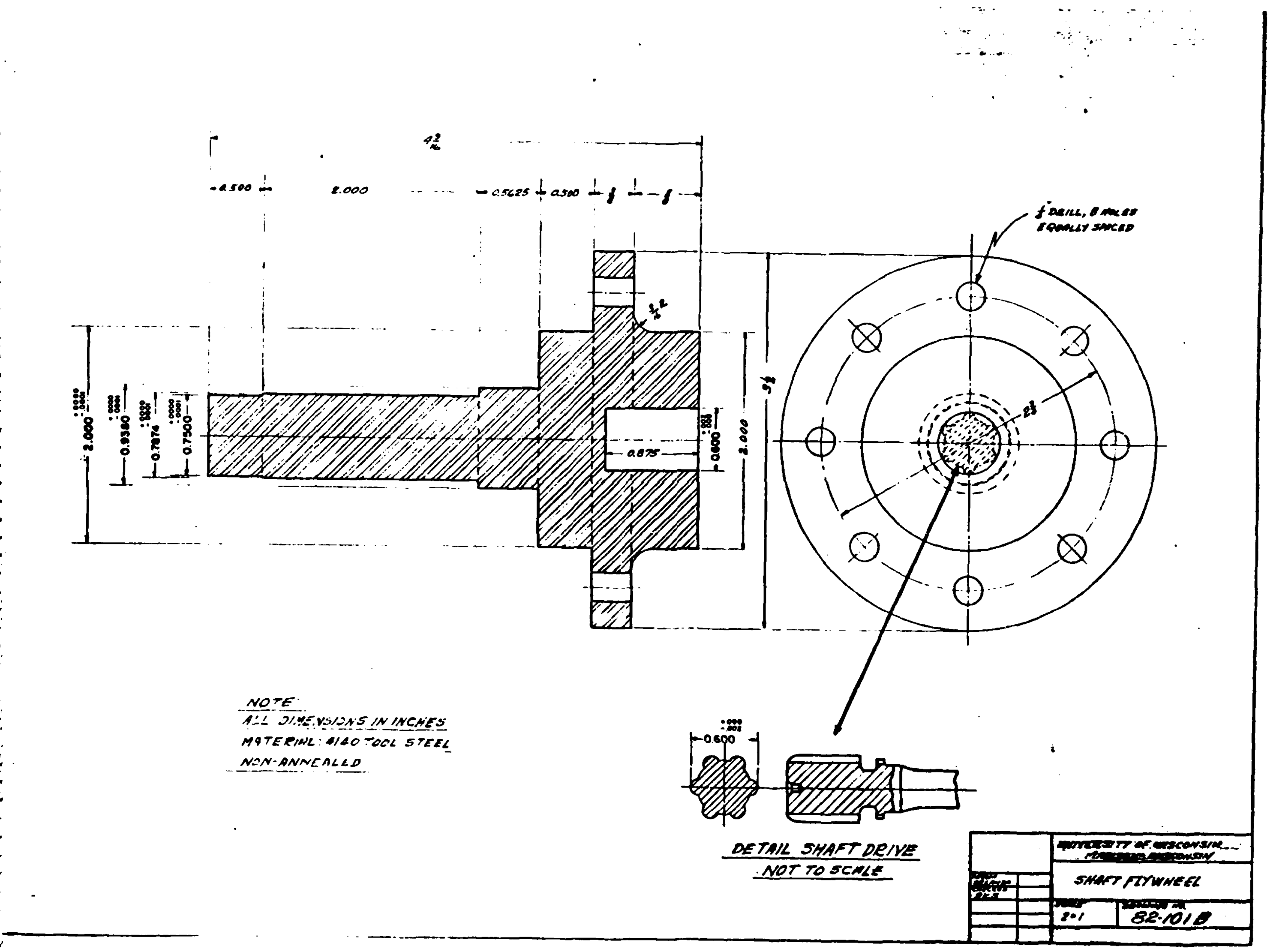


NOTE:
All dimensions in inches
Tolerance .001 unless otherwise noted

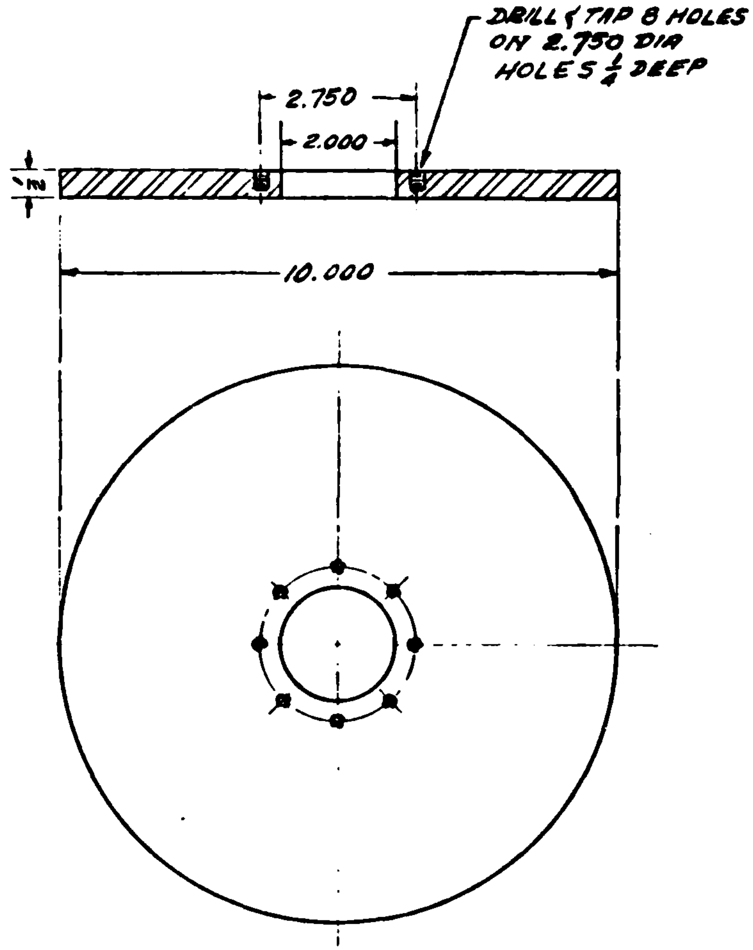
		UNIVERSITY OF WISCONSIN	
APPROVALS	DATE	FLYWHEEL HOUSING DETAIL	
DRAWN	8-9-82		
CHECKED	8-10-82	SCALE 1/2=1, FULL	DRAWING NO 82-101A



UNIVERSITY OF WISCONSIN		
HUB ASSEMBLY FLYWHEEL		
Full	Orlando	
OS		9-14-82

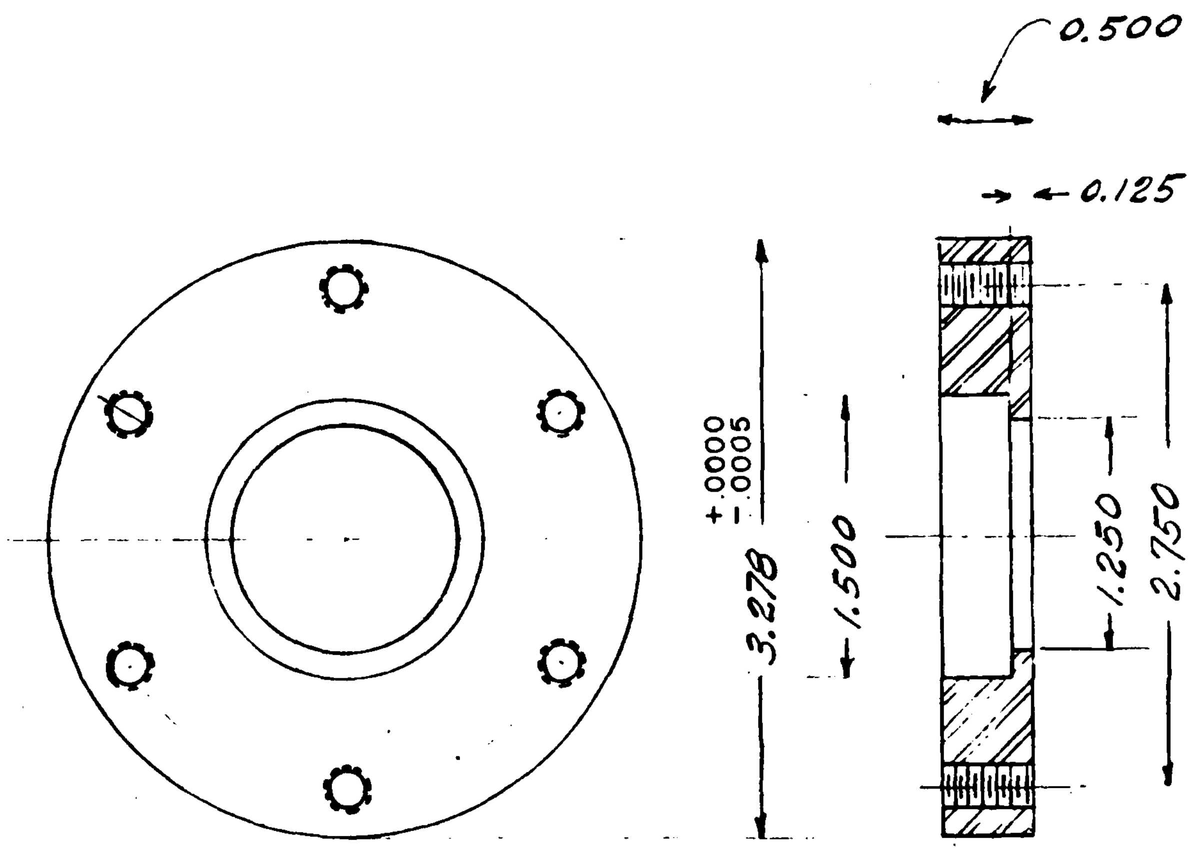


2.000
0.9380
0.7874
0.7500
0.500
2.000
0.5625
0.500
0.875
0.600
3½
¼ DRILL, 8 HOLES
EQUALLY SPACED
NOTE
ALL DIMENSIONS IN INCHES
MATERIAL: 4140 TOOL STEEL
NON-ANNEALED
0.600
DETAIL SHAFT DRIVE
NOT TO SCALE
UNIVERSITY OF WISCONSIN
SHAFT FLYWHEEL
2:1
82-101 B



NOTE:
WHEEL IS 4340 STEEL.
STEEL IS NORMALIZED AND
TEMPERED TO APROX. 35 HRC.

UNIVERSITY OF WISCONSIN		
TITLE FLYWHEEL		
SCALE FULL	DRAWN Erlando	DRAWING NO.
CHECKED	APPROVED	DATE 10-18-82



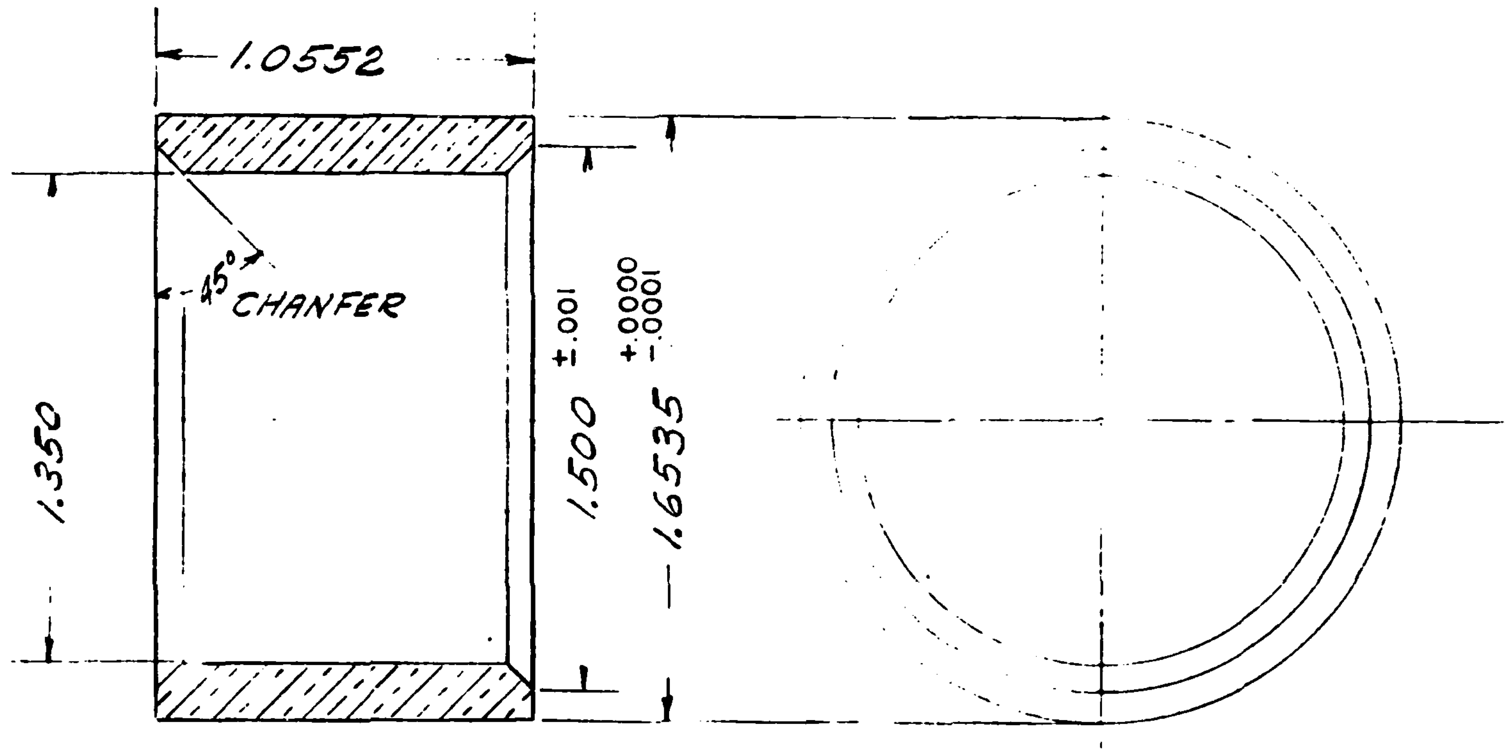
DRILL & TAP 6-HOLES
EQUALLY SPACED FOR ¼-20 M.S.
ON 1.375 CIRCLE

MATERIAL: STEEL

ALL DIMENSIONS IN INCHES

UNIVERSITY OF WISCONSIN		
TITLE BEARING RETAINER FLYWHEEL		
SCALE FULL	DRAWN ORLANDO	DRAWING NO 82-101-C
CHECKED	APPROVED	DATE 9-1-82

SHOULD MATCH INNER RING

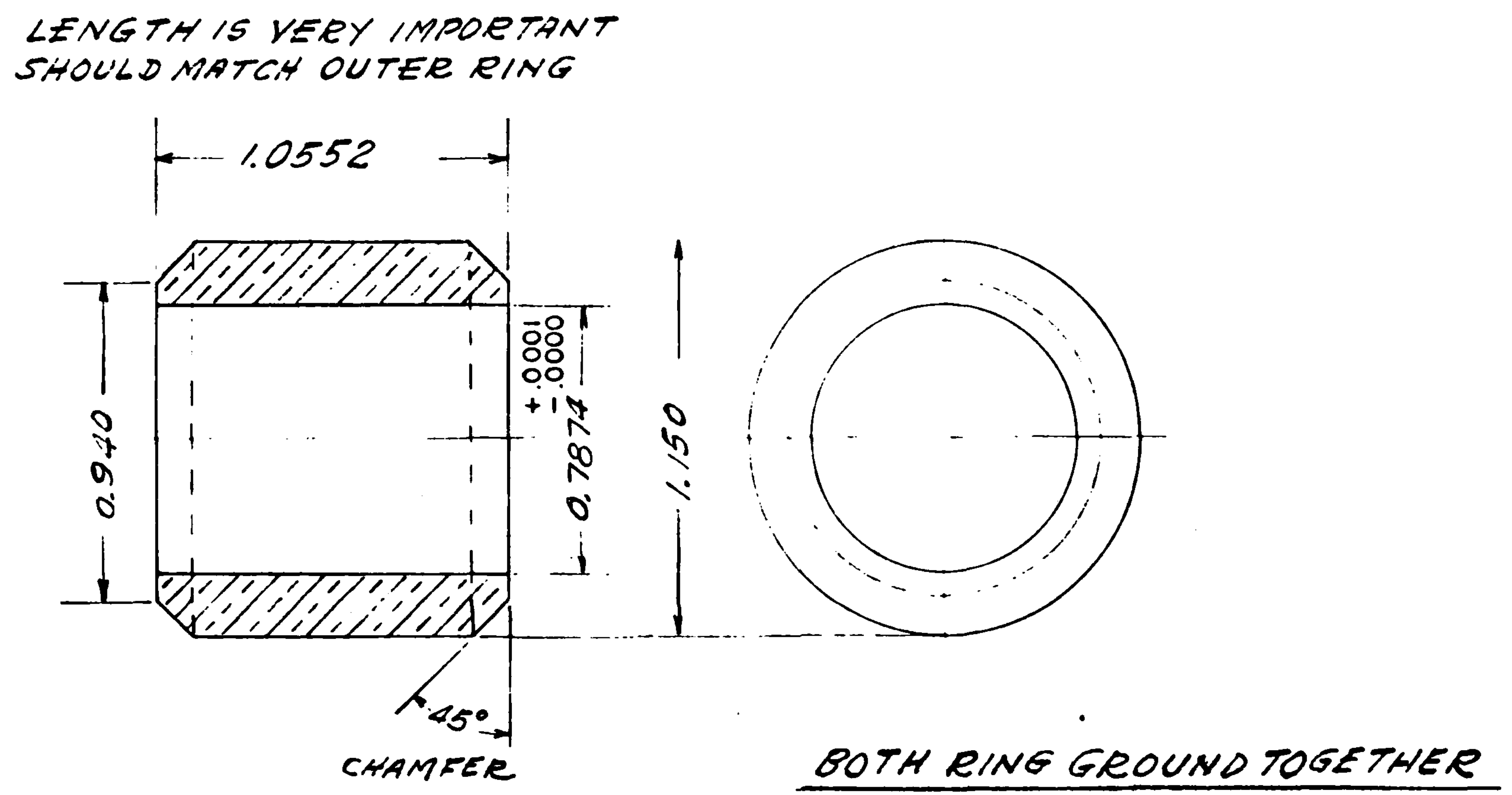


NOTE:

SPACERS TO BE MADE OF BRASS OR SOFT STEEL

ALL DIMENSIONS IN INCHES

UNIVERSITY OF WISCONSIN		
TITLE SPACER OUTER RING FLYWHEEL		
SCALE 2:1	DRAWN Orlando	DRAWING NO 82-101-D
CHECKED	APPROVED	DATE 9/1/82



NOTE:
SPACERS TO BE MADE
OF BRASS OR. SOFT STEEL
ALL DIMENSIONS IN INCHES

		UNIVERSITY OF WISCONSIN
APPROVALS	DATE	SPACERS-INNER FLYWHEEL
Drawn ORlando	9-1-82	
Checked		SCALE 2:1 / DRAWING NO. 82-101-E

END

DTIC

7-86